A CASE STUDY OF HIGH-SCHOOL STUDENT SELF-REGULATION RESPONSES TO DESIGN FAILURE

by

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For Emily, Nathan, and Laura—

learn to look backward and look forward

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Author: Jackson, Andrew, M. PhD
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Although design is part of everyday experience, increased proficiency in managing and reflecting while designing signify greater proficiency as a designer. This capacity for regulation in design is crucial for learning, including from failure experiences, while designing. Failure and iteration are integral parts of design, with potential cognitive and psychological ramifications. On the one hand, failure can be framed as a learning experience that interrupts thinking and evokes reflection. On the other hand, it can be detrimental for confidence and motivation or derail the design process. Based on similarities between design and self-regulation, I articulate a framework whereby responses to failure might be regulated by beginning designers. Then, this case study applies the framework to describe the experiences and perspectives of beginning designers as they work and fail, illuminating issues of failure in design and the extent of their self-regulation.

The in situ design processes of four teams was examined to describe self-regulation strategies among student designers. Analysis was conducted with two methods: linkography and typological thematic analysis. Linkography, based on think-aloud data, provided a visual representation of the design process and tools to identify reflection, planning, and critical moments in the design process. Typological analysis, based on think-aloud data, follow-up interviews, and design journals, was used to investigate specific strategies of self-regulation. The complementary methods contribute to understanding beginning designers' self-regulation from multiple perspectives.

Results portray varied trajectories in design, ranging from repeated failure and determination to fleeting success and satisfaction. Class structures emerge in designers' patterns of planning and reflection. These highlight the contextualized and evolutionary nature of design and self-regulation. Furthermore, linkographic evidence showed a beginning sense-making process,

followed by oscillating phases of forward and backward thinking, to various degrees. Moments of testing, both successes and failure, were critically connected in the design process.

Thematic analysis identified 10 themes, aligning with the self-regulatory phases of forethought, performance, and reflection. The themes highlight how regulation in forethought is used to shape performance based on past iterations; meanwhile, the identification and attribution of failures relays information on how, and whether to iterate. Collectively, thematic findings reinforce the cyclical nature of design and self-regulation.

Design and self-regulation are compatible ways of thinking; for designers, the juxtaposition of these concepts may be useful to inform patterns of navigating the problem-solving process. For educators, the imposition of classroom structures in design and self-regulatory thinking draws attention to instructional design and assessment for supporting student thinking. And for researchers of design or self-regulation, these methods can give confidence for further exploration.

CHAPTER 1. INTRODUCTION

Design problem-solving is invariably a part of everyday life—when aspiring to change the current situation to a better one, "how things *ought* to be"; balancing conflicting criteria and limited resources to choose the best solution; or just applying common sense to navigate a problem. Having engaged in this process, you are a designer according to Simon (1996), Koen (2003), or Lawson and Dorst (2009), respectively. Design problems—ill-structured tasks that require analysis, synthesis, and evaluation to generate solutions (Dubberly, 2004; Goel & Pirolli, 1992; Jonassen, 2000)—are also specifically addressed in a number of disciplines, such as engineering, computer graphics, or architecture. And while design has historically been associated with these disciplines, the practices of design are increasingly being adopted in business (Brown, 2008; Rowland, 2004), policy making (Norman & Stappers, 2015), social change (Manzini & Coad, 2015), and other disciplines (Lahey, 2017; Steinert, Taeumel, Cassou, & Hirschfeld, 2012; Strobel, 2010). However, when tackling an open-ended design problem, do designers anticipate instances when the design will not work or are they caught by surprise? And, taken in hindsight, are these design failures a valuable learning experience, dissected to uncover new insights, or are they ignored?

Even while design practice is spreading, further experience by itself does not lead to proficient design (McDonnell, 2015), let alone the specific abilities to overcome failure and improve while designing. Design problems "require greater commitment and self-regulation by the problem-solver" (Jonassen, 2000, p. 80). Illustrating various stages of development , design research has often investigated performance among progressive levels of expertise, from novice to expert (e.g., Atman et al., 2007; Cross & Clayburn Cross, 1998; Dorst, 2003). Expert designers demonstrate constant refinement in the design process, iterating and evolving their understanding of both the problem and solution (Dorst & Cross, 2001). These observations concur with other evidence suggesting expert designers' comfort in managing the design process, regardless of ambiguity (Daly, Adams, & Bodner, 2012). Included in expert regulation strategies are opportunities for reflection: "getting better at design reasoning…requires not only opportunities to exercise design reasoning, but also opportunities to inspect and introspect about behavior, perspectives, worldviews" (McDonnell, 2015, p. 117). Cross and Clayburn Cross (1998) also noted that "it is perhaps the nature of expert performance that formalized, step-by-step procedures… become subsumed into a more seamless, personalized way of working" (p 147). In other words, a designer's capacity for self-regulation—that is planning, managing, and reflecting on their work—is a crucial element in fostering their ability to learn from failure and continually develop design expertise.

Inconsistent responses to failure illustrate a gap between beginning designers' abilities and the reflective conditions for obtaining design proficiency. A previous investigation of elementary engineering students responding to failure showed wide reactions—positive and negative responses, in both action and affect (Lottero-Perdue & Parry, 2015). One the one hand, some students returned to the design process. On the other hand, some students missed learning from failure due to giving up, losing interest, or moving on without planning or reflection. Inexperienced designers are found to miss these lessons from failure in other studies as well. These beginning designers:

> …act with little or no awareness of what they are doing, do not articulate what knowledge they know or need to know to further their investigations, and pay scant attention to the progress they make, obstacles they encounter, or design values that influence their decisions. They can fail to review steps they have taken or to examine the assumptions underlying their framing of the design problem. They leave their knowledge of their designs and design process implicit and unarticulated, which can limit their ability to transfer knowledge they have accumulated to new situations. (Crismond & Adams, 2012, p. 772)

Up to the undergraduate level there is evidence that beginning designers tend not to iterate as much as they do with more experience (R. S. Adams & Fralick, 2010), meaning fewer attempts are made to improve ideas. Cognitive misrepresentation of the design process may lead students to work step-by-step rather than in a cyclical, iterative way. In addition to responding inconsistently, beginning designers may dwell on negative aspects of experiencing failure.

Even encountering failure does not necessarily mean that learning will occur: how the designer frames the experience will determine whether or not it is a benefit. A stream of evidence suggests that learning can be realized by working through failure in open-ended problem solving; failure helps students investigate underlying principles which are assembled for later understanding (Kapur, 2008; Kapur & Bielaczyc, 2012; Loibl & Rummel, 2014). When framed negatively though, failure experiences can be detrimental to beginning designer's confidence, motivation, and interest (Kapur, 2011; Lottero-Perdue & Parry, 2017a). Even taking into account other psychological needs, the motivational trajectories of engineering students described by Trenshaw, Herman, Green, and Goldberg (2014) hinged on experiences of failure or success. Whether or not beginning designers realize benefits from failure experiences may require curricular scaffolding of the experiences and structures for reflection, exceeding the attention given to other design pedagogies.

In light of unused learning opportunities, or even negative consequences, of experiencing failure, further understanding the experiences and perspectives of beginning designers as they work and fail, is necessary to inform design education and shape pathways for the development of design expertise. Among existing studies, little attention has been directed to secondary technology and engineering courses as a context for investigating students' capacity to plan ahead, respond to failure, and reflect in design. Design abilities are a learning outcome for these courses (International Technology Education Association, 2007), not just a pedagogy. Therefore, resolving the seeming disconnect between the nature of design—it is emergent, requiring failure and iteration—and novice designer behavior is an educational aim. Neither has attention been paid to the precise nature of how student interactions and behavior when failing facilitate learning (Kapur & Kinzer, 2009; Pathak, Kim, Jacobson, & Zhang, 2011), nor the "roles of meta-cognitive and self-regulatory functions in productive failure" (Kapur & Bielaczyc, 2012, p. 77). Furthermore, existing studies have been predominantly quantitative, focusing on problem-solving performance at the expense of investigating situational aspects and students' experiences. Where it has been included, embedded qualitative analysis has uncovered a glimpse of students' work and experience (e.g., Kapur, 2010), hinting at the utility of in-depth qualitative investigation.

1.1 Statement of Purpose

The purpose of this case study is to describe the use of self-regulation strategies among high-school design students, in the face of design failures while completing an iterative engineering design challenge. The design processes of eight students are used to illustrate these issues among beginning designers, framing the work as an instrumental case study (Stake, 1995). My interest was in students' strategy use, where I adopt Zimmerman's (2000) cyclical framework of self-regulation—forethought, performance, and self-reflection—as a way to characterize how students plan, perform, and respond to design failures. This qualitative study investigated self-regulatory strategies in secondary technology and engineering courses; the study is situated in the gap of existing research just described, by its attention to secondary technology contexts, focus on the impact of student regulation on learning, and qualitative focus on student experiences.

The context of this study is part of a larger study to develop engineering curriculum (Jackson, Zhang, Kramer, & Mentzer, 2017), chosen in this research for 1) the frequency of encountered failure, and subsequently required iteration, in the design challenge, and 2) the teacher participants' openness for our ongoing research. Whereas the larger study encompassed a greater number of students, I provide an illustration of the design experiences of a few student designers, recounting their plans, decisions, and reactions while completing an iterative challenge. While describing the failures and intentions of these designers, I will make connections that allow the reader to develop a more nuanced view of reality (Flyvbjerg, 2006; Gary Thomas, 2011). Next, the guiding questions which led the research design and beginning of the investigation are described. Then, the bounds of the case and the study context are described in greater detail.

1.2 Guiding Questions

As understanding grows and events unfold in qualitative inquiry, the guiding questions are refined to turn attention to significant issues. Stake (1995) wrote of progressive focusing: "the researcher makes a flexible list of questions, progressively redefines issues, and seizes opportunities to learn the unexpected" (p. 29). Gary Thomas (2011) similarly described *prima facie* questions, which are refined through the literature review and observations to arrive at the final questions of the study.

My initial attention in this study was directed at the planning, management, and reflection done by beginning designers in an iterative design challenge. These behaviors are called upon throughout the design process. Although, more specifically, I was interested in how self-regulation processes are shaped by conceptions and experiences of failure in design. The interplay between past or present experiences of failure has the potential to ripple through future cycles of iteration in design.

The primary guiding question was "How do beginning designers use self-regulation when navigating failure and iteration?" Two related questions add texture to the investigation:

1. What are the patterns of self-regulation used by beginning designers when navigating failure and iteration?
2. What self-regulatory strategies do beginning designers employ in practice?

1.3 Case Context

These initial questions were shaped by my prior exposure to the case, and therefore my assumptions about the student design experience. Here, I describe the case context, including how I believe the selected technology and engineering curriculum offered a lens into the self-regulatory practices of beginning designers as they encounter failure. This discussion forecasts my positionality, and role in developing the curriculum, which is described more fully in Chapter 3. Throughout the development of the instructional context, iteration was foregrounded as part of the student design experience. While self-regulatory strategies may be a function of the design context, this design experience required holistic iteration, due to the fabrication materials, and made failure manifest. Together, these characteristics raise the likelihood of seeing student regulatory strategies in play.

The chosen setting for this research was a recently developed curriculum unit introducing and exploring soft robotics within secondary technology and engineering education (Jackson, Zhang, et al., 2017). The soft robot design unit lasts about eight hours (or one week of 90 minute classes daily) and was conceptualized to increase STEM participation, especially among girls, by changing student paradigms for robot design. Instructional development of the unit, and feasibility testing in classroom settings has commenced with support from the National Science Foundation (Grant DRL-1513175). Soft robotics is a "young" (Bao et al., 2018, p. 229) field of engineering application which uses compliant, soft, and bioinspired systems to solve robotics problems (Trimmer, 2013). Due to the material differences of these robots, compared to traditional robotic systems of rigid parts, soft robots have distinct advantages for 1) handling objects that are fragile or change shape, 2) designing from biological inspiration, and 3) interacting in human-centered applications (Majidi, 2013; Trimmer et al., 2013; Wang, Chen, & Yi, 2015). The design of soft robots involves balancing a variety of decisions—modes of actuation, strength, cost, fabrication simplicity, and others—to perform effectively (Rus & Tolley, 2015).

1.3.1 Iterative Design

The design-based instruction begins by providing students with a scenario to construct a robotic gripper to assist in an agricultural setting (see Appendix A). Given this setting, the gripper's abilities to handle fragile produce with accuracy and without damage are required. Teachers delivered a presentation to describe the underpinning scientific principles of pneumatics and demonstrate fabrication steps for the entirely soft, air-powered robots: casting a two-part silicone elastomer and adhering fabric to 1) create an enclosed air chamber and 2) constrain the robot motion to curve (see Figure 1 and Figure 2). The presentation and conversation illustrated that, as grippers are inflated, a bending actuation results from inner air chamber configuration and differences in elasticity of robot parts. Following the discussion, students were given the opportunity to explore potential variables in soft robot fabrication through hands-on research, before building a gripper they design. A reconfigurable mold was provided, which allowed the rapid manipulation of length and air chamber configuration, and allowed experimentation with individual gripper fingers before constructing a completed gripper (Figure 3). In this way, the lesson supported student iteration in their design work. And material constraints required holistic iteration, where students fabricated a new design for each phase rather than tinkering with the previous attempt. The student enacted design experience in this lesson, and my conceptualization of design in this research study, encompassed both conceptual and process design. Through repeated phases of making, students had the opportunity to manipulate the configuration of their soft robotic gripper, as well as the process for fabrication (guided by teacher demonstration and provided resources).

1.3.2 Evident Failure

Past inquiry into the efficacy and experience of the soft robotics curriculum revealed the prevalence of failure in this context. Aligned with the interest in exploring reactions to student failure, it was important that failure be embedded in the context and perceptible. In a similar example, Dorst and Cross (2001) described the challenge of investigating creativity in design: "there can be no guarantee that a creative 'event' will occur" (p. 426). However, in our case, the

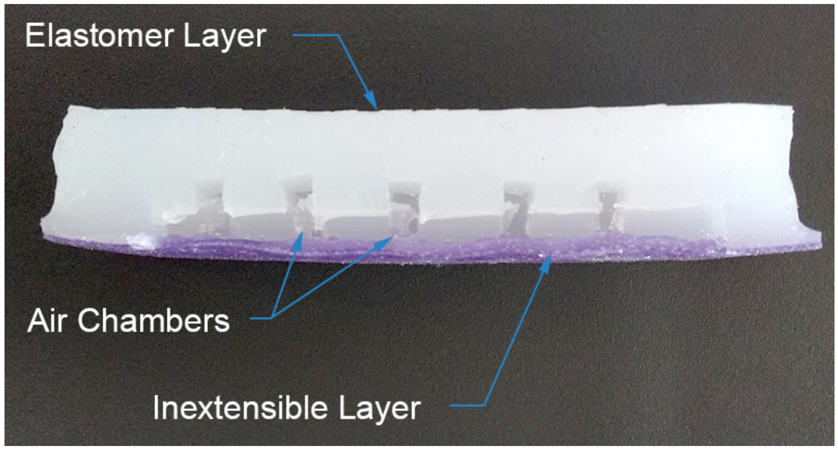

Figure 1. Soft robot finger cross section with air chambers, elastomer and inextensible layers.

Figure 2. Soft robot finger inflation demonstration showing curved motion. Due to layer flexibility differences and internal air pressure, the gripper actuation is constrained to a curve.

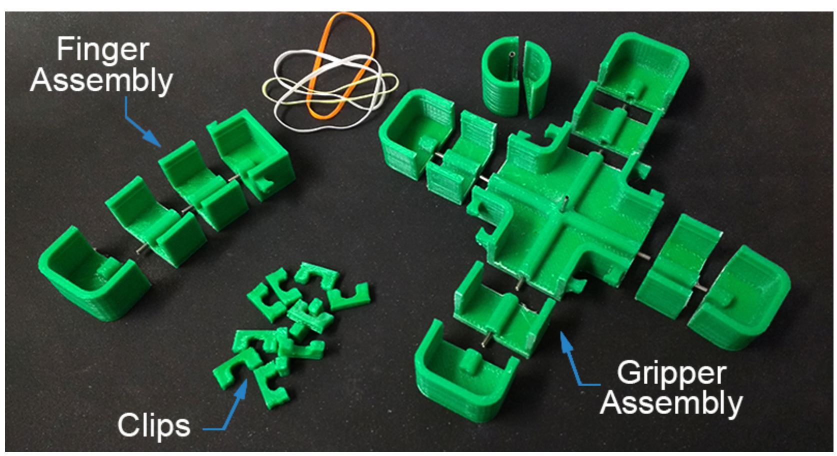

Figure 3. Reconfigurable mold for soft robot fabrication. Parts can be composed to make a soft robot finger or entire gripper. Additional pieces can be used to modify the length. Air chamber configuration is configurable by clip placement. Customized design of the gripper will lead to variations in performance (see Zhang, Jackson, Mentzer, & Kramer, 2017).

research team had received feedback regarding the challenges of successfully fabricating a gripper during the first year of implementation. Sometimes this failure was due to an improper fabrication process when the silicone would fail to cure. At other times, the final produced gripper failed to meet the design requirements provided in the project brief.

Upon visiting classes at the end of the first year to observe the success of student robot designs in person, another graduate student and I tested the final grippers of 54 design teams (Zhang et al., 2017). Only 29 (54%) were able to successfully complete the design challenge to simulate holding agricultural goods without dropping them. In addition, we saw multiple modes of failure, stemming from different steps in the fabrication process: clogged air chambers, an insufficient seal to the fabric, uneven curvature of the gripper, or even air leaks from bubbles in the silicone. Through our discussion and analysis, we could infer changes that may lead to success. Yet, with only nascent exposure to soft robots, I do not think I could have immediately diagnosed these failures or reflected on the changes needed to overcome them—only passed judgment that the design was unsuccessful. My own learning illustrates that a combination of evident failure and careful reflection and iteration are needed.

1.3.3 Case Assumptions

Based on my past involvement, I entered observations of the case with several assumptions. First, I assumed this would be a challenging experience for beginning designers. The materials are new for students and the fabrication process is sensitive to small changes in procedures. Subsequently, I assumed that some of the designs produced by students would not work or would not work as well as expected. My experience in the development of this project was beneficial here, as I was able to perceive potential problems in the fabrication process that may have been overlooked by beginning designers. The anticipation of potential failures drew my attention to the design situation and reactions of the team as they later encountered failure. Third, linked to inoperable designs, I also assumed students would have a chance to make several versions of the soft robot artifacts and vary their designs. In this process I hoped that students would uncover the fabrication and design details to change in order to produce a successful design. Yet, to whatever extent attempts to improve were taken by these designers, examination of the experience would offer insight into self-regulatory practices. Said another way, I expected the first designs would not work as well as the students hoped and that dialog would articulate the desired improvements. These self-reflections would come to frame the next attempts, including criteria for success in the design.

1.4 Study Contributions

Undertaking this study, I recognize that generalizability is not the power of case study (Gary Thomas, 2011). From such an intense observation of a case, a small sample, I am concerned with offering “exemplary knowledge” (Gary Thomas, 2011, p. 211) and conclusions from my reconstruction of the experience (Stake, 1995, p. 85) without “overarching generalizations” (Goldschmidt, 2014, p. 27). Complementary to the broader investigation of engineering perceptions, which the curriculum unit is situated in, my work highlights detail of the design experience, particularly failure experiences, as navigated by beginning students. If failure can be emphasized in design as a learning experience, but students’ reactions to failure are varied, it is important to describe current thinking in context. “Good descriptions of actual design behavior [are] essential to progress in understanding thinking as it occurs in real-life design practice” (Goldschmidt, 2014, p. 19). Therefore, a main contribution of this study is the descriptive account of the perspectives and regulatory strategies beginning designers take to respond to failure in design. Furthermore, the closeness of observations conducted herein—following along with a few selected design teams for the duration of their in situ experience—offers a perspective of design that educators are unable to obtain while constrained to manage an entire class of students. This scholarship can benefit design researchers and educators by expanding understanding of beginning designer conceptions and reactions to experiences of failure and iteration in design.

Next, through analysis of the contexts and experiences of these designers, this research invites transferability to support improvement in design education. Extending the assertion that failure is not always treated as a learning experience by all students, it is important to identify ways to resolve this opposition. In reporting the vicarious experience, I consider the impact of contextual factors on beginning designers’ process and failure experiences. The account may feel as though it overlaps the reader’s story or situation or past students (Tracy, 2010, p. 845). I also posit instructional ideas without claiming they are “best practices,” only those which seem to work in these contexts and which might augment “professionals’ judgment in unique situations and deepen our understanding of complex educational practices” (Frelin, 2015, p. 598). Taken together the portrayal of design behavior and analysis given hereafter intimate ways, as design educators, that we can support our own students as they encounter failure.

1.5 Summary

The process of designing is widespread, and growing. Yet, design problems are naturally ambiguous and challenging. In design, there is extensive information to manage—including instances when ideas do not work—and there is mixed evidence about beginning designers' capacity to respond to such failures. Therefore, further scholarship is necessary to extend our understanding of student strategies for managing design and failure if we are to appropriately teach "designerly" ways of thinking. A new engineering curriculum for soft robot design has been developed and implemented, with ongoing evaluation. In this context, iteration is prefigured into the curriculum and failure has been prevalent; this setting presents an opportunity to focus attention on student designers' self-regulatory practices surrounding failure. Guiding research questions have been described, whereby this study will share student experiences—describing their journey of design—and broaden understanding of beginning designers' moves as they encounter design failure in the iterative design of soft robots.

CHAPTER 2. REVIEW OF LITERATURE

As indicated in Chapter 1, there is a disparity in beginning designer behavior and the proficiency that comes by navigating failure and successive iteration in design; through experiences and reflection and increased understanding about processes, designers begin to develop expertise (Lawson & Dorst, 2009). The inherent tension between supporting students to be successful and letting them learn from failure experiences is explored in this chapter. This chapter is organized into three sections: first, a review of literature to identify circumstances and conditions to learn from failure; second, an overview of self-regulation theory; and third, the presentation of a framework to integrate self-regulation and failure experiences in design practice. The theoretical framework for self-regulation in failure experiences is brought to bear on the present research situation and provides direction to further understand the cognition and performance of designers as they encounter failure.

2.1 Learning from Failure

For technology and engineering education, an understanding of design is a learning outcome for students, not just a pedagogy (International Technology Education Association, 2007). Included in the *Standards for Technological Literacy* are

STL #8. Students will develop an understanding of the attributes of design.

STL #11. Students will develop abilities to apply the design process.

STL #12. Students will develop the abilities to use and maintain technological products and systems.

In many ways, the characteristics of design imbue how design is taught in schools. Design problems are open-ended with more than one right answer, ambiguous, and constructive—both literally, in hands-on activities, and figuratively, in terms of knowledge generation (Goel & Pirolli, 1992; Grubbs & Strimel, 2016). Iteration, reflection, and learning while designing are crucial for nurturing designers (Dorst, 2003; McDonnell, 2015; Schön, 1983).

In light of this focus on iteration as an important attribute of design, failure would seem to be an accepted, even expected, part of design and a learning opportunity—designers iterate and revise designs because the first idea did not work as well as expected. Indeed, Crismond and

Adams (2012, p. 750) identified "learning while designing" as a key performance aspect of design and "managed and iterative design" and "reflective design thinking" as patterns of informed design work which might be attainable by design students. There even exists a broad base of literature related to failure analysis which informs engineering practice (e.g., the journal *Engineering Failure Analysis*).

Yet, there is additional evidence that beginning students tend not to value iterating as highly as they do with more experience (R. S. Adams & Fralick, 2010). Paradoxically, even though students will grow from having more design experiences, their encounters with failure while designing may be a barrier to confidence and persistence despite its significance. "Successes raise mastery expectations; repeated failures lower them, particularly if the mishaps occur early in the course of events" (Bandura, 1977, p. 195).

Given the seeming disconnect between realities of design—failure and iteration—and the goal to bolster design learning, it is important that we investigate experiences of design failure and key elements in making failure a learning experience in design. Among the design cognition studies just described, synthesis has not been related to failure specifically. Therefore, to better understand what is known about failure in design for secondary students, or learning from failure, I conducted a systematized literature review. Review findings such as these can inform design teaching practice and may highlight gaps in existing research related to design learning. Such a synthesis of design research, as it relates to student learning from failure, may present the same benefits, especially by identifying opportunities to support beginning designers. The purpose of this systematized review, then, was to search, select, and analyze existing literature on learning from failure in design-related education. The systematized review was guided by two questions:

1. What research and evaluation methods have been used to study failure in design?
2. What are key elements in making failure successful for learning in design?

Next, the nature of systematized reviews and methods for conducting the search are described. Following the description of the search protocol, I map the territory of existing research to characterize the nature of previous investigations, before turning to a thematic synthesis of results.

2.1.1 Systematized Review

The procedures for searching, selecting, and analyzing content related to the research questions were patterned off recommendations by Borrego, Foster, and Froyd (2014) for conducting systematic literature reviews in engineering education. This review is limited in several aspects, described later, relative to full systematic reviews. Nonetheless, it is still useful to understand the methodological goals of a systematic review. In contrast to traditional literature reviews, systematic literature reviews approach the analysis of existing work in a “transparent, methodical, and reproducible” manner (Borrego et al., 2014, p. 46). Petticrew and Roberts (2008) recommend asking whether a systematic review is needed before conducting any new research, but especially recommend one “when a general overall picture of evidence in a topic area is needed to direct future research efforts” (p. 21) or when key questions about people’s experiences remain unanswered despite existing research on the topic.

Liberati et al. (2009) identified key characteristics and steps of systematic reviews:

> The conduct of a systematic review comprises several explicit and reproducible steps, such as identifying all likely relevant records, selecting eligible studies, assessing the risk of bias, extracting data, qualitative synthesis of the included studies, and possibly meta-analyses. (p. 2)

On the other hand, systematized reviews include these features to a lesser degree or may not include the complete characteristics of a systematic review (Grant & Booth, 2009). Specifically, I conducted a narrower search than might be done with additional resources and have not included a formal validity assessment of the included studies, therefore I stop short of labeling this work a systematic review. Still, given an interest to “map…the relevant intellectual territory in order to specify a research question which will further the knowledge base” (Tranfield, Denyer, & Smart, 2003, p. 207) and the dispersion of design research (noted especially by Crismond & Adams, 2012), there is methodological fit with the aims of this research.

2.1.1.1 Search Parameters and Results

While some information can be determined before beginning, the research development and search processes are iterative (Borrego et al., 2014; Tranfield et al., 2003). Journals related to design, technology education, or engineering education were identified as potential sources for further searching based on my past experience. I chose to search using the EBSCO Education

Source database because it indexed a majority of the journals of interest such as *Cognition and Instruction, Journal of Engineering Education, Journal of the Learning Sciences, Journal of Technology Education, International Journal of Technology and Design Education, and Journal of Pre-College Engineering Education* (and others). In addition, two conferences with proceedings (the American Society for Engineering Education [ASEE] and IEEE Frontiers in Education [FIE] annual conferences) were used for manual searching with the chosen keywords.

To begin identifying search parameters, two articles by researchers known to have investigated "design failure" or "productive failure" were chosen and assessed.[1] From these "seed" articles, keywords and themes were identified to inform the complete search and data extraction phase. Search terms were chosen such that the article must reference some variant of failure (e.g., fail, impasse); a STEM education, STEAM education, design education or problem-solving context; and learning or instruction (see Appendix B for the complete search query). The EBSCO database search returned 757 results which were then narrowed (see Figure 4) based on whether the source was in English (75 removed) and from an academic journal or conference (142 removed). The search strategy for ASEE and FIE was modified only slightly, to fit the available search fields, returning 18 and 66 cases, respectively.

The 624 results were further narrowed by removing duplicates (8 removed) and limiting the analysis to articles within the past 10 years, 2008 to 2017, for recency of articles and to focus my resources (301 removed). Abstracts, and papers as needed, were then screened according to three predetermined criteria, which are listed with exclusion criteria:

1. The paper should describe a primary investigation of students' or teachers' experience with failure—this might be a learning activity or students' psychological underpinnings with failure perceptions as a main construct.
   Not included: papers about using failure cases for learning or analysis of prior work.
2. The context should be K-16 STEM or design education involving a complex problem.
   Not included: out-of-school learning or well-structured problem with a single approach.

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[1] Kapur and Bielaczyc (2012) and Lottero-Perdue and Parry (2017a)

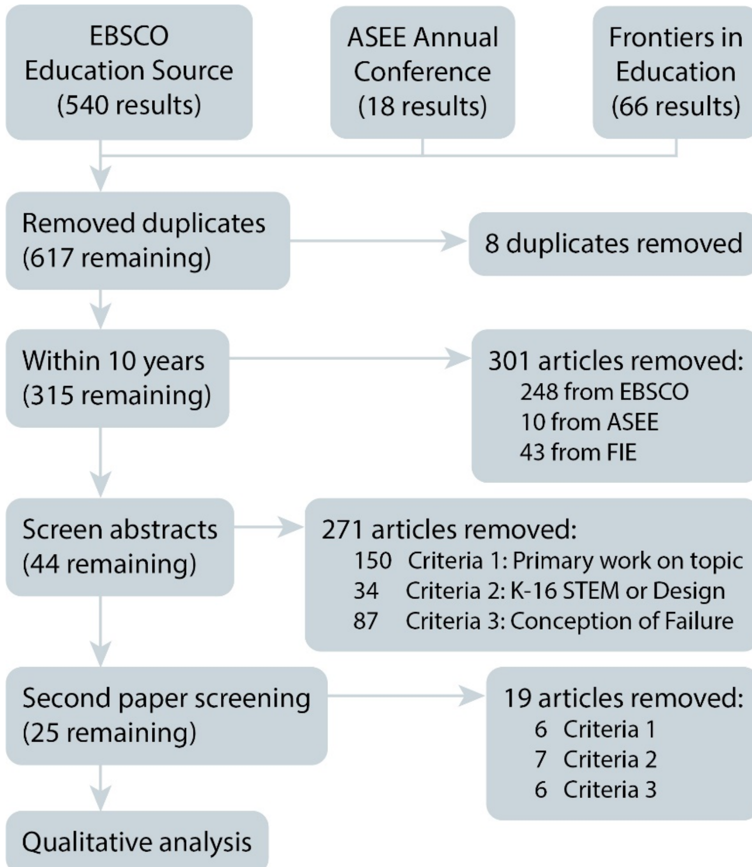

Figure 4. Flowchart of search results and selection by criteria based on PRISMA guidelines (Liberati et al., 2009). Eight hundred forty-one initial results were narrowed through removing duplicates, non-journal and non-conference work, and screening criteria. After closer reading 25 cases were included in the final analysis.

3. The conception of failure should relate to iteration, redesign, or learning in an activity or challenge. Psychological constructs of failure (e.g., failure avoidance) are equivocal in this regard, hence included.

   Not included: papers related to failing schools, failing grades, or students failing classes.

These filters retained 44 results and were followed by a closer read of the articles to ensure that they met the criteria. In this closer read, 19 articles were removed based on the same criteria; definitions of the criteria had crystallized from seeing examples and non-examples and these articles were in fact off topic, out of K-12 contexts, or about academic failure. Finally, two random samples of papers from the entire collection were inspected to check for consistency of inclusion: I inspected 20 articles (6%) with 95% agreement to the original selection (one article was a false negative, it had been previously removed and was subsequently included), and a professor of engineering education inspected 31 articles, 10%, with 100% agreement. In sum, 25 articles were identified and used for the final synthesis.

2.1.1.2 Data Extraction

Once the final selection of articles was determined, I performed data extraction with the combination of a data extraction form to identify the study, context, and research design (Rana, Robert, Eugene, Philip, & Richard, 2011; Tranfield et al., 2003) and annotations to identify predominant themes across articles (Meese & McMahon, 2012). Key elements of the data extraction form were aligned with the interest to map existing literature on learning from failure—for example, grade level and STEM discipline. Other categories emerged through review of several articles, such as how failure was operationalized for the research (if it involved attempted problem solving, hereafter enacted failure, or investigated the psychological aspect of failure). Finally, much of the extraction form was dedicated to describing the research design including qualitative or quantitative approaches taken, philosophical and theoretical perspectives, sample size, data sources (e.g., surveys, interviews, or design journals), analysis methods and key findings. A complete list of elements is presented in Figure 5.

Study Identification

- Title
- Authors
- Year of Publication

Study Context

- Grade Level: Elementary, Middle School, High School, Undergraduate
- Discipline Area: Science, Technology, Engineering, Math, design, unspecified
- Failure approach: Enacted Failure, Psychological
- If project-related: Collaborative, Individual, Not Applicable
- Describe the Context

Research Design

- Theoretical Framework
- Qualitative or Quantitative
- Study Design (e.g., experimental, quasi-experimental, or qualitative methodology used)
- Sample Size: Students *n*, Teachers *n*
- Information Sources (i.e., what scales or variables were used)
- How are Outcomes Measured?
- Analysis Methods (e.g., open coding, MANCOVA)
- Key Findings
- Failure leads to…
- Threats to Study
- Quality Assessment: Good, Great, Excellent
- Notes/Connections

Figure 5. Data extraction form elements.

2.1.2 Mapping Results

The 25 included articles, with extracted grade level, disciplinary context, and research design are included in Appendix C. Mapping the results addresses the first research question, "What research and evaluation methods have been used to study failure in design?" In the past 10 years, empirical investigations of failure with complex problem-solving environments (e.g., design, technical content, or new learning) have been evenly distributed over time (Figure 6) and source material (Table 1). The articles came from 15 different journals or conferences with varying aims; for example, generalized sources were related to instructional design, while more technical sources included engineering or science education research journals.

Two broad research contexts are in line with Criteria 1—research studies were conducted on enacted failure (*n* = 19) in open-ended or complex problem solving situations and psychological factors (*n* = 6) related to the experiences of failure. Studies of enacted failure dealt with student or teacher actions in response to experiences of failure or difficult problem-solving in the classroom. On the other hand, psychological approaches involved surveys which assessed constructs such as "fear of failure" (Pantziara & Philippou, 2015) or "failure avoidance" (Plenty & Heubeck, 2013) in connection with attitudinal and motivational elements; and some used qualitative methods to richly portray the students' voices (Hutchison-Green, Follman, & Bodner, 2008). The studies characterized as psychological tended to use a diverse backdrop of motivational theories—for example, Attribution Theories (Upadyaya, Viljaranta, Lerkkanen, Poikkeus, & Nurmi, 2012), Self-Determination Theory (Trenshaw et al., 2014), or Self-Efficacy Theory (Hutchison-Green et al., 2008). The enacted studies either did not explicate a theoretical framework or followed the pattern of Productive Failure introduced by Kapur (2008). The analytical method chosen in each study also coincided with the context of study: the majority of enacted problems used experimental or quasi-experimental designs to study the efficacy of an instructional intervention. Psychological investigations tended to use correlational methods such as structural equation modeling. A few studies (*n* = 6) were wholly qualitative investigations. Yet, embedded qualitative data were sometimes used to elaborate on quantitative findings; when it occurred, this embedded analysis often took the form of contrasting the discourse between students in the conditions being studied.

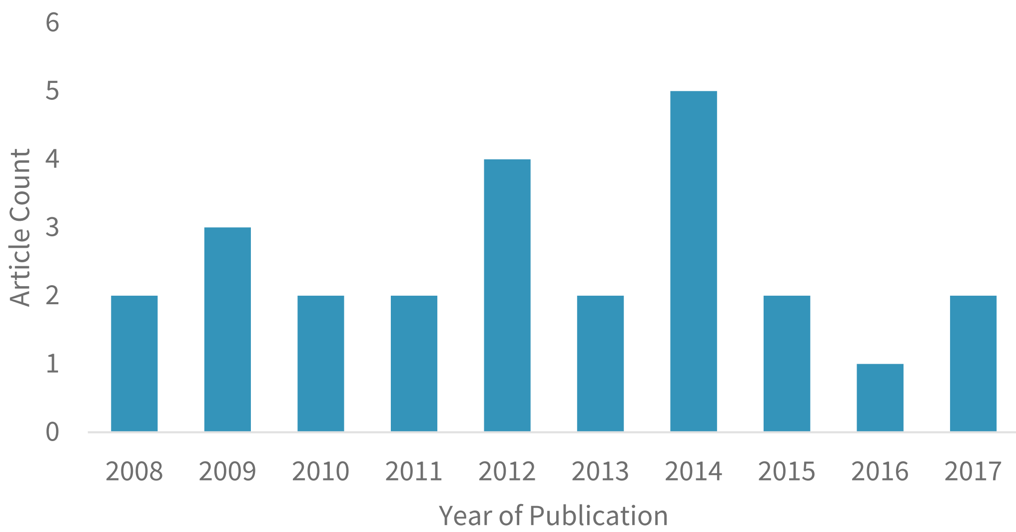

Figure 6. Number of articles in final selection by year.
Note: To focus researcher resources when conducting the search, only results between 2008 and 2017 were included.

Table 1. *Number of Failure Articles in Systematized Selection by Source.*

Article Source	Selected Articles
ASEE Annual Conference	3
Cognition and Instruction	1
Cognitive Science	1
Educational Psychology	1
European Journal of Engineering Education	1
Instructional Science	6
International Journal of Computer-Supported Collaborative Learning	2
International Journal of Engineering Education	1
International Journal of Science and Mathematics Education	1
International Journal of Science Education	1
Journal of Educational Technology Systems	1
Journal of Engineering Education	1
Journal of Pre-College Engineering Education Research	2
Journal of the Learning Sciences	2
Social Psychology of Education	1

Mapping the coverage of research by grade and STEM discipline reveals differential coverage of the existing research (Figure 7). A few articles (n = 4) considering the responses and perceptions of teachers to design failure were aggregated based on the grade-level and disciplinary focus of the teachers participating in the study. Most articles (n = 11) related to mathematics and took place at the high school or undergraduate level. Coverage of engineering courses excluded high school classrooms and technology education was not well represented in this research stream. Only one study investigated difficulties in a technology context (Pan, Kuo, & Strobel, 2010), although one study did mention that the advanced technology leveraged in their science course was a challenge for students (Trueman, 2014). The engineering design process naturally embeds failure and, while efforts are being made to bring this instruction earlier in school experiences (e.g., Engineering is Elementary), it remains primarily taught by secondary Technology and Engineering Educators. Further research in this authentic setting would meaningfully add to the present discussion.

2.1.3 Thematic Synthesis

Following a description of the coverage offered by existing research, I turn to a synthesis of findings and implications for design teaching, to address the second research question, “What are key elements in making failure successful for learning in design?” Synthesis of the 25 articles began by reading each article, annotating key elements and findings, as well as writing a

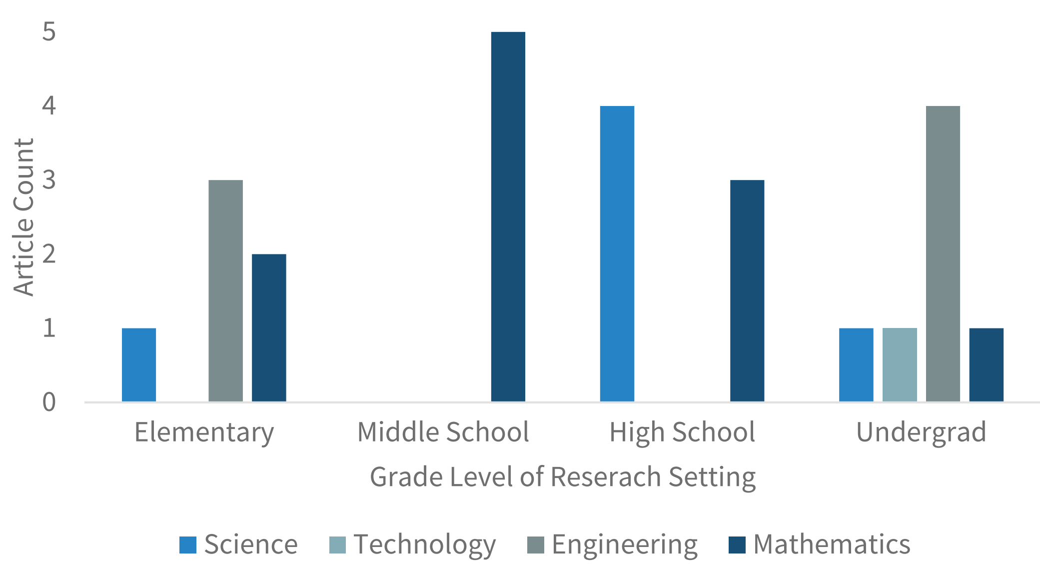

Figure 7. Mapping of included studies by disciplinary context and grade level.

summary of the research design, weaknesses, findings, and implications. Emergent patterns were identified and revised through two phases of reviewing the articles. As articles were reviewed the patterns were populated with excerpt statements, providing evidence from multiple points in literature. This synthesis across papers, the emerging patterns or themes, addresses the second aim of this review—to identify key elements for making learning from failure successful. Five themes of these articles include:

1. Varied meanings of failure,
2. Collecting positive and negative reactions to failure experiences,
3. Failure as a mechanism to uncover key concepts for students,
4. Failure induces thoughtfulness in problem solving, and
5. Implications for the classroom climate and communication about failure.

Using evidence and quotations from the 25 articles, these are described in the next sections. In these sections, recommendation for improving discussions of failure in the classroom are provided.

2.1.3.1 Theme 1: Varied Meanings of Failure

An important background to making failure a learning experience is the conceptualization of what failure means in STEM and design courses. Examples of failure among these research articles were alternately process-oriented or solution-oriented. Process-oriented definitions were that failure might be taken to mean reaching an impasse, a point where students do not know how to proceed (e.g., Kapur, 2010). Such experiences with failure were seen in multiple points in the design problem-solving process: getting stuck coming up with new ideas (Pan et al., 2010); failing to take into account design criteria (Lottero-Perdue & Parry, 2017a; Sleezer, Swanson, & Bates, 2016); or not being able to find a workable solution on their own (e.g., Kapur & Bielaczyc, 2012). Students' processes were also categorized as inefficient (Kapur & Kinzer, 2009). Process-related failure in problem solving may also manifest as students reject an idea or abandon their initial work (Kapur, 2010). Solution-oriented definitions described failure when the solution was incorrect or the designed product was not successful or as successful as later ideas (e.g., Lottero-Perdue & Parry, 2017a). This conceptualization of process- and solution-oriented failures is not exclusive; it is used to broaden perceptions and understanding of when failure is encountered in problem solving.

The definition of failure within technology and engineering design contexts was contrasted with the connotation of failure in other educational contexts. For example, students and teachers were familiar with messages about failing grades or schools, which were to be avoided. However, in technology and engineering design contexts, teachers felt that the design process accounted for failure by its iterative nature and once students knew they would have a chance to improve, failure was more manageable (Lottero-Perdue & Parry, 2015; Lottero-Perdue & Parry, 2017b). The definition of failure may also be socially constructed. Hutchison-Green et al. (2008) pointed out that students' judgments on success can be strongly influenced by peer performance—being faster to obtain a solution or contributing more than others were seen as signs of success—especially when the context was unfamiliar.

2.1.3.2 Theme 2: Student Reactions to Failure

Across the articles reviewed, a number of positive and negative reactions to failure were identified. This theme includes student reactions broadly, both in terms of later performance (measured outcomes) or next actions and attitudes. Failure, by itself, is not believed to be the mechanism which promotes learning (Loibl & Rummel, 2014). Rather, positive student reactions are linked with later success. Student reactions to failure were well summarized by Lottero-Perdue and Parry (2015) who characterized observed reactions as either positive or negative, and based on action or emotion. Specific positive examples included trying again, analyzing the failure, asking for help, or not adopting a failure identity. Negative examples included giving up, making thoughtless design changes, ignoring information, or copying the work of others.

A majority of research (13 out of 25 articles, 52%), including Kapur's work (e.g., Kapur, 2008), reported empirical evidence that effort on problem solving, even if students failed to arrive at a solution, activated prior-knowledge and enhanced understanding and transfer of learning following instruction (also, Loibl & Rummel, 2014; Trueman, 2014; Westermann & Rummel, 2012). When encountering failure without structure in the learning environment, student conversations and process steps become a type of structure to supplement the lack of instruction. Kapur and Kinzer (2009) observed the organic generation of feedback cycles in problem-solving conversations; Trenshaw et al. (2014) described a type of recommitment and return to effort that can occur; and Lottero-Perdue and Parry (2017a) described the positive trend of students and teachers returning to the design process when ideas did not work. Pathak et al.

(2011) observed a team with problem-solving supports, which succeeded easily, and one without support, which struggled, reporting that iteration after failure "induces reflective reasoning practices" (p. 72). Despite struggling, the team without support also leveraged new resources, such as modeling and peer support, to foster understanding. Thus, the process of failure and designing new solutions seems to support flexibility, a broad search for ideas, and reflective practice in response to failure.

Yet, without guidance students have reported low confidence following problem solving, which is an important limitation to address. Students who have encountered failure may not perceive learning or growth, despite increased performance. Trueman (2014) and Kapur (2011) both reported cases where students' confidence did not correspond to their high performance. Of the articles which conducted psychological investigations, some negative reactions to failure were identified: attributing failure to external factors adversely affected interest and performance of students (Upadyaya et al., 2012) and students sometimes disengaged or felt uncomfortable asking for help following failure (Akatugba & Wallace, 2009). Additionally, fear of failure led students to focus on performance instead of concept mastery (Pantziara & Philippou, 2015). Other negative reactions included being biased to favor initial ideas rather than trying new approaches (Kapur, 2014b; Sleezer et al., 2016). This negative reaction emphasizes the need for sincere reflection and improvement for changing failure to a learning experience. Furthermore, students may not acknowledge the progress they have made, as found in interviews by Hutchison-Green et al. (2008). Student and classroom factors may influence student responses to failure, and students may exhibit mixed responses.

2.1.3.3 Theme 3: Failure as a Mechanism for Uncovering Key Concepts

A consistent hypothesis for the mechanism whereby failure leads to student learning is that solution attempts lead to exploration of key concepts and later consolidation and understanding (Kapur & Bielaczyc, 2012). In the reviewed articles, initial encounters with failure were a mechanism for students to activate prior knowledge and process key concepts, whether through contrasting examples of failure and success (Kapur & Kinzer, 2009; Loibl & Rummel, 2014) or an instruction phases following student exploration (e.g., Kapur, 2008). Consider the aforementioned contrast between a team who succeeded easily—without discerning key components or encountering the boundaries of their knowledge—and a team who failed and persisted—necessarily constructing understanding and monitoring salient details of the environment. The lack of apparent structure or success seemingly highlighted key elements for successful problem-solving when they were presented later (Kapur, 2008, 2010; Kapur & Kinzer, 2009). Said another way, "Initial activation of cognitive resources [in failing] might have primed them to *receive* the conceptual and representational structure in [a] follow-up structured activity" (Pathak et al., 2011, p. 71). Such an ability "to perceive and structure a complex, ill-structured problem is a critical dimension that seems to differentiate experts from novices" (Kapur & Kinzer, 2009, p. 39). However, experimental research has demonstrated that in order to catalyze such focus, students need to be aware of their failures. In a context where failure was not obvious to learners, there was no benefit to beginning with student exploration compared to being instructed on a correct solution (Matlen & Klahr, 2013). Akatugba and Wallace (2009) articulated two consequences that resulted when students become used to concentrating on solutions or merely employing algorithms to derive their answer quickly: they overlooked details of the subject content or became inflexible problem-solvers. The reviewed articles offer multiple perspectives showing that the haltering process of failure can be a benefit to student understanding of key concepts.

2.1.3.4 Theme 4: Failure Induces Thoughtfulness in Problem Solving

The previous theme of exploring key concepts as a result of failure relates to the next theme, which contrasted routine, or automatic, approaches to problem solving, and thoughtful processes induced by failure experiences. In well-structured environments, or when given instruction, students quickly converged on a solution and made fewer solution attempts (Kapur, 2014b). In these situations, reflection and evaluation did not happen spontaneously (Kapur, 2014a; Pathak et al., 2011) and team dialog was focused on solution development, rather than using problem analysis or criteria to undergird the process (Kapur, 2008; Kapur & Kinzer, 2009). As students gained experience, they reported spending less time dealing with planning and task management in problem solving (Plenty & Heubeck, 2013). A positive explanation for this time shift is that the task structures require less cognitive demand due to their past experiences, however, this lower demand may come at the sacrifice of attention given to the situation. The process may lead to "success" but it is at the lack of conceptual understanding, and subsequently an inability to transfer learning.

In contrast, when students were required to navigate failure to develop the process, they built “gradual sophistication in understanding” (Pathak et al., 2011, p. 71). Team dialog when working on open-ended problem solving, and encountering failure, was more complex: it included more transitions and reflective feedback loops to evaluate solutions than in routine problem-solving contexts (Kapur, 2008; Kapur & Kinzer, 2009). These initially ineffective approaches were seen as a waste of time by some (Akatugba & Wallace, 2009), though these problem-focused conversations built a tentative structure for problem solving, which could be reinforced through instruction (Kapur, 2008, 2010). Failure necessarily encouraged the exploration of different solutions, which was related to improvement in performance (Kapur, 2014a, 2014b) and is an important characteristic of good design. This iteration affords students a chance to make judgments and understand what works, and why, more so than in routine problem solving. Encountering failure can also lead to a search for alternatives and additional knowledge resources to overcome the failure. Students reported seeking inspiration and additional resources, being persistent in trying different ideas, seeking advice, and relying on design requirements to overcome difficulty (Pan et al., 2010).

Failure can also lead to greater metacognition, reflection, and regulation in problem solving. Pathak et al. (2011) noted students’ systematic and reflective approaches emerged following ill-structured situations. When presented with a new situation, “[students] compared and contrasted the two topics…without any explicit instruction or demand by the problems” (p. 71). Westermann and Rummel (2012) demonstrated a reciprocity between letting students struggle in problem solving and increased metacognition and reflection. When student problem exploration was aided with a script that promoted process monitoring and reflection, performance increased significantly compared to traditional problem solving. The pairing of failure experiences and reflective practice increased the likelihood of learning. Yet, even among teams that encounter failure, there was a spectrum of reactions and performance. Students may negatively try the same design again or thoughtlessly iterate (Lottero-Perdue & Parry, 2015). They may pursue an inefficient “guess-and-check” approach (Kapur & Bielaczyc, 2012). In order for failure to be a learning experience, students need to analyze failure, understand what happened, why it happened, and how to move forward (Lottero-Perdue & Parry, 2017b)—to self-regulate their performance.

2.1.3.5 Theme 5: Classroom Climate and Communication about Failure

Finally, the review indicated that teachers need to foster a classroom culture that embraces failure and learning together. Through student interviews, survey responses, and classroom observations, research related to learning from failure shows the importance of classroom communication for appropriately framing failure experiences. The relationship between students' motives and values and the experiences of failure is multi-faceted (Plenty & Heubeck, 2013). Failure has troubling connotations in many educational contexts, and beginning teachers reported a tendency to avoid using the word "failure," instead labeling it as "mistakes" or "revisions" (Lottero-Perdue & Parry, 2017b). Teachers also had an inherent tension between embracing learning from failure and trying to scaffold students to success (Berglund et al., 2009; Lottero-Perdue & Parry, 2017b). Depending on feedback offered or the nature of the task, students may not even be aware of their failures (Matlen & Klahr, 2013). However, in order for students to receive the benefits that follow from failure, reflection, and iteration, failure needs to be both experienced and clearly identified. In fact, the response to failure has led to stronger team and student-teacher relationships (Trenshaw et al., 2014) and more questioning and engagement from students (Berglund et al., 2009). Especially in light of differences between perceptions of learning and actual performance, Trueman (2014) recommended that conversations turn to helping students identify learning from failure, pointing out that learning has indeed taken place. With more experience, teachers felt more confident in discussing failure. This development included using deliberate language to identify failure and professional judgment which tailored interactions to the design context and needs of each team (Lottero-Perdue & Parry, 2017a).

The use of failure words needs to be associated with failed designs, not failing students (Lottero-Perdue & Parry, 2017a; Upadyaya et al., 2012) to lead to these positive reactions, disentangling existing meanings of failure with how it can be leveraged in the design process. A consistent positive message for student teams is to persevere and try new approaches in problem solving. An increase in performance was realized when teachers set and repeatedly emphasized the expectation "that students are not expected to be able to solve the problem" right away but should work hard on multiple approaches (Kapur, 2011, p. 575). This encouragement can take place until students have sufficiently explored the problem space, before more formal instruction. Drawn from the review articles, some other specific strategies for fostering a positive climate are

1) to readily talk about learning from failure, 2) give students autonomy to set goals and make paths for themselves (there is not a "right" answer), and 3) provide opportunities for formative check-ins and feedback on a project (Sleezer et al., 2016). In past experience, these failure check-in and feedback opportunities were touchstones that encouraged students to take risks and make forward in their design work.

Precursory to failure experiences, there needs to be an atmosphere of trust in the classroom—trust that the instructor will provide guidance and that it is a safe place for learning. Given this climate, failure experiences can turn to learning opportunities and help students recommit to their work (Trenshaw et al., 2014). Upadyaya et al. (2012) described how teachers' attributions for the cause of success or failure affected student perceptions. This evidence, in line with attribution theories, showed that teachers should take care to attribute success or failure to matters within student control, or risk lowering student interest. Decreased fear of failure, an artifact of good classroom climate, was also related to greater confidence and interest and mastery goal approaches for students (Pantziara & Philippou, 2015). Finally, in describing instructional design for productive failure, it is necessary to find "a sweet spot where students are challenged yet not frustrated and remain sufficiently engaged in problem solving" (Kapur & Bielaczyc, 2012, p. 50). This "sweet spot" means knowing who our students are, what resources they have, and designing problems of interest.

2.1.4 Review Summary

The purpose of this systematized review was to investigate extant knowledge about learning from failure, including previous approaches undertaken to study failure. I narrowed the initial search results from 624 articles to 25 articles focused on K-16 STE(A)M or design experiences with failure, conceptualized as a learning opportunity. Further, I mapped the research space, identifying a gap in inquiry related to technology and engineering in secondary education (Figure 7). While these courses are focused on design learning outcomes, the impact of failure in the design process has not been studied here. Five themes were identified, which show varied interpretations and reactions to failure, mechanisms whereby failure can operate as a learning tool (uncovering key concepts and triggering reflection), and ideas about communication surrounding failure. The results of this synthesis show that failure is prevalent in the STEM and design learning spaces and has the potential for promoting deeper learning.

2.1.4.1 Limitations

As a systematized review, this work has inherent methodological limitations. I acknowledge the limitation of using one database, and selected conference proceedings. A larger proportion of search results from ASEE were retained by the criteria than from other search locations. However, this is likely because the search terms used only targeted the title, session, or topic fields, leading to more accurate, yet narrower, results. Also, based on the chosen criteria, papers which offered paradigmatic arguments or generated frameworks related to failure were not included. The resulting themes need to be interpreted in light of this gap; in terms of theory building, these works represent a critical perspective which could be incorporated in future work. In short, other criteria and databases may yield different results.

This work also represents my perspective for conducting the search and codifying the results. However, iterations with the search (and checks for sentinel articles within the search results) and several passes over the final selection of papers should enhance the reliability of the final selection. Furthermore, personal and external review showed consistency in applying the selection criteria. The study findings remain informative for considering educative failure in K-16 STEM or design courses.

2.1.4.2 Future Research Directions

Systematized reviews permit the organization of research to identify gaps and future directions. Certainly, each limitation just described represents an opportunity to improve this work: expanding the search, incorporating paradigmatic literature, and leveraging multiple researcher perspectives to substantiate the findings. The scarcity of research on failure at the intersection of technology and engineering education and secondary classrooms is surprising, given the focus on design teaching, and an opportunity for future work.

The recommendation by Borrego et al. (2014), to distinguish between assertions and empirical support among the sources, underscores three further directions for future work. First, follow-up on the long-term impacts of problem-solving difficulty on student confidence would be beneficial since students have reported low confidence without guidance in ill-structured problem-solving phases (e.g., Kapur, 2010). Second, research alluded to metacognitive and self-regulatory practices emerging from failure, though the research was more often focused on performance improvements, and this hypothesis requires further investigation. As stated by Kapur and Bielaczyc (2012):

> There is some indication from the group discussions that the productive failure design [of instruction] gave students opportunities to engage and develop their meta-cognitive and self-regulatory functions, which in turn are critical components of learning and problem-solving expertise…. Examining the collaborative problem-solving processes to unpack the roles of meta-cognitive and self-regulatory functions in productive failure is an area that future studies would do well to examine further. (pp. 76-77)

The third and fourth themes identified in this review indicate the hypothesis—that failure promotes reflection and develops metacognition—is widespread. The third opportune research direction is the need to follow-up on the interactional dynamics of students while problem solving, as mentioned by Kapur and Kinzer (2009, p. 40) and Pathak et al. (2011, pp. 70-71). Close analysis of these interactions would perhaps uncover differentiating characteristics that are useful to explain variation, even among teams in the same instructional model, and rich details about the students' experiences. Yet, few studies provided qualitative investigation of student perspectives.

Failure is embedded in the design process. These experiences can show more profound impacts on motivation than other psychological aspects of the classroom (Trenshaw et al., 2014). Previous literature has also contained little specific instruction on how to help students include failure in design or realize positive consequences of failure (Sleezer et al., 2016). However, as indicated by the themes in this work, the conceptualization of failure in design contexts is unique and offers the potential to promote learning. Moreover, the attention to failure experiences herein, and identification of research trajectories, is beneficial for advancing positive conversation on helping students learn from failure and begins to extend our understanding of failure for learning.

2.2 Self-Regulation Theory

As previously mentioned, evidence of beginning designers suggests an inability to identify salient details, frame the design space, or suitably evaluate ideas. The iterative nature of the design process is intended to capitalize on information from early design ideas, successful or not. The design process requires attention to both the features of design and ever-changing environment (Salustri, Eng, & Rogers, 2009). Are beginning designers able to identify and incorporate such details to improve their work? Due to limitations of beginning designers' abilities, the roles of metacognition and self-regulation in design contexts have been questioned and recommended as areas of inquiry (Kapur & Bielaczyc, 2012).

This section describes self-regulation, its subcomponents, and how it is embedded in performance. I also describe previous approaches to measure self-regulation. The definitions presented here are theoretical in nature, representing idealized conceptions for self-regulation in practice, which are foundational to the framework presented in the next section.

2.2.1 Defining Self-Regulation

Self-regulation is the "self-generated thoughts, feelings, and actions that are planned and cyclically adapted to the attainment of personal goals" (Zimmerman, 2000, p. 14). Three distinct phases identified by Zimmerman (2000) further clarify the meaning—forethought, performance/volition control, and self-reflection. Approaching a task begins with mental anticipation, thoughts are then brought to action, reactions to the performance are rendered and interpreted. Information cascades through the three phases; they successively inform each other and adjustments are made in current and future attempts (Zimmerman, 2000; Zimmerman & Cleary, 2006). In self-regulation theory, information and thoughts can shape behavior both proactively or reactively; expectations in advance of an event change our strategy, whereas reflection-in-action can lead to changes or internalized thinking afterwards.

Self-regulation is a skill, not merely achieved through determination or willpower (Bandura, 2006). It involves learning to monitor behavior and environmental contexts, set goals, and use a variety of strategies to carry out tasks. Yet, achieving consistent self-regulatory skills also "requires instilling a resilient sense of efficacy as well as imparting skills....This involves training in how to manage failure" (Bandura, 2006, p. 17). Binkley et al. (2012) and Pellegrino and Hilton (2012) not only characterize self-regulation as a skill, but as an important 21st Century Skill, critical for success in the current and future workplace. Further signifying the importance of self-regulatory skills, while some task specific strategies may be learned and applied for self-regulation, it is largely generalizable (Pajares, 2006).

Self-regulation theory has been influenced by social cognitive theory (Bandura, 1977), clarifying the socio-contextual influences on self-regulated thinking (it is shaped by personal, behavioral, and environmental factors; Schunk, Meece, & Pintrich, 2014; Zimmerman, 2000). Subsequently, self-efficacy, a tenet of social cognitive theory, is included as part of the forethought phases of self-regulation. Initial beliefs about our capacity to perform a task undergird or undercut our planned behaviors and motives. Metacognition, “thinking about thinking” or the monitoring of cognitive processes, and reflection are also similar to one another and encompassed by self-regulation. Indeed, Barak (2010) conceptualized self-regulated learning as the intersection of cognitive, metacognitive, and motivational domains. Self-regulated learning is a related term which I take as the application of self-regulation to realize learning outcomes and use interchangeably with self-regulation.

Self-regulated learning and self-directed learning are also often used synonymously, and need to be disentangled. Several authors have compared the use and background of these two terms (Cosnefroy & Carré, 2014; Jossberger, Brand-Gruwel, Boshuizen, & van de Wiel, 2010; Loyens, Magda, & Rikers, 2008; Saks & Leijen, 2014). Both terms relate to autonomy, goal setting, and performance analysis (Saks & Leijen, 2014). However, self-regulation is a more specific term in several ways. First, self-regulated learning is a learner characteristic while self-directed learning also encompasses the design of the learning environment (Loyens et al., 2008). Second, to be a self-directed learner requires self-regulation, yet the opposite is not true (Cosnefroy & Carré, 2014). Self-directed learning entails the planning of a learning trajectory, broadly, with self-regulation necessary for the performance of each included element. And third, self-regulation is at a micro level, concerning “execution of a task” (Jossberger et al., 2010, p. 418) while self-direction is at the macro level and concerns “a learning trajectory as a whole” (p. 419). Cosnefroy and Carré (2014) also provided three dimensions, based on the research backgrounds of these concepts, to distinguish self-regulation and self-directed learning. Following this guide, self-regulation as operationalized in this research is related to 1) educational psychology more than adult education, 2) adolescents more than adult learners, and 3) teacher generated learning activities (in contrast to completely student-led activities). Based on differences between these terms in literature, self-regulation, rather than self-directed learning, was chosen as the lens to interpret students’ reactions to design failure.

2.2.2 Self-Regulation Phases and Subcomponents

Within the three phases of self-regulation, several subcomponents have been organized and empirically investigated (see Table 2). Information or strategies from each phases of self-regulation, or any subcomponent, can affect later processes in the cyclical stream of self-regulated thinking. As previously mentioned, forethought comprises the activities in preparation for a task, performance of the task can be accompanied by monitoring and strategy use, and self-reflection takes place after the activity to diagnose and inform future task performance. I briefly describe the hallmarks of each subcomponent in this milieu of factors.

Forethought is further delineated to include task analysis activities of goal setting and strategic planning, and self-motivational beliefs. Effective *goal setting* involves the formation of specific and challenging goals; such goals enable evaluations and reflection later on (Zimmerman, 2000). *Strategic planning* is the advanced selection of strategies to accomplish the task. Non-cognitive factors play a role in establishing expectations and plans prior to performance. Four such self-motivational factors are identified. *Self-efficacy* is personal belief about ability to accomplish a task (i.e., “Can I do this?”). *Outcome expectations* are beliefs about the results of performing a task (i.e., “Will this lead to the desired results?”). Both affect task choice, motivation, and persistence (Bandura, 1977; Betz, 2006; Carberry, Lee, & Ohland, 2010; Jackson, 2018). *Intrinsic interest* is enjoyment or perceived value from the task. Motivational and interest theories, and common sense, establish the role of interest in task choice (Eccles et al., 1983; Kier, Blanchard, Osborne, & Albert, 2013; Su, Rounds, & Armstrong, 2009). *Goal orientation*—whether the task is done for mastery or performance and other related beliefs—also

Table 2. *Phase Structure and Subprocesses of Self-Regulation from Zimmerman (2000, p. 16).*

Cyclical self-regulatory phases		
Forethought	Performance/volitional control	Self-reflection

Task analysis
  Goal setting
  Strategic planning
	Self-control
	  Self-instruction
	  Imagery
	  Attention focusing
	  Task strategies
		Self-judgment
		  Self-evaluation
		  Causal attribution

Self-motivational beliefs
  Self-efficacy
  Outcome expectations
  Intrinsic interest/value
  Goal orientation
	Self-observation
	  Self-recording
	  Self-experimentation
		Self-reaction
		  Self-satisfaction/affect
		  Adaptive-defensive

shapes performance trajectories. Process-related goals, in contrast to performance goals, are also seen to relate to intrinsic motivation, creativity, and optimism (Beghetto, 2006; Pajares, 2006).

During performance, attending to the quality of execution is a way to learn from performance. Self-control strategies relate to focus on and quality of performance. Self-observation elements relate to monitoring and learning from performance. *Self-instruction* is self-talk, physically or mentally, to describe how to perform the task. *Imagery* is the formation of mental models or visualizations of effective task performance. *Attention focusing* is a collective term for approaches to minimize distractions and enhance focus on the task (e.g., working in a quiet location). *Task strategies* are the variety of approaches to perform the task in its constituent parts. These strategies might include note taking, help seeking, collaboration, testing understanding, or time management. *Self-recording* is capturing performance progress including any potential contextual factors leading to results. "Without [self-recording], selective memory of successes and failures come into play. Often our beliefs about outcomes do not faithfully reflect the outcomes" (Schunk et al., 2014, p. 159). *Self-experimentation* is the process of manipulating aspects of performance to identify patterns for performance improvement. Self-observation strategies can lead to greater personal understanding and performance.

The final phase, self-reflection, includes judgment and reaction elements. These activities involve assessing and explaining performance outcomes, respectively. This reflective phase follows performance and allows us to internalize information, impacting future forethought and performance. Lin, Hmelo, Kinzer, and Secules (1999) stated, "Reflective thinking ultimately involves understanding one's own process of learning" (p. 46). *Self-evaluation* is the comparison of actual performance to performance goals. In the absence of clear, specific goals, such comparisons are made normatively (Zimmerman, 2000). This shift deemphasizes earlier regulatory processes and self-observation to use social comparison; it will tend to "emphasize negative aspects of functioning instead of the positive ones" (Zimmerman, 2000, p. 22) and can cause students to overlook personal success (Hutchison-Green et al., 2008, p. 186). *Causal attribution* is developing an explanation for the performance outcomes, successes or failures. Explanations have three typical dimensions; they are 1) internal or external, 2) stable or unstable, and 3) controllable or uncontrollable (Driscoll, 2005, p. 236). External, stable, and uncontrollable causes remove the locus of control from the learner and can lead to helplessness; on the other hand, attributions for internal, controllable causes can lead to recommitment, learning, and determination for the next try. Self-beliefs and performance contexts frame these explanations for success or failure. For example, a failure that takes place in unusual test circumstances may precipitate attributions to external causes or someone with high confidence may attribute their success to effort and ability. “Negative self-evaluations do not decrease motivation if people believe they can improve” (Schunk et al., 2014, p. 160). Yet, without support or intervention from the teacher, students may not stop to reflect on their thinking or may have difficulty doing so (Lin et al., 1999).

Judgment and interpretation of performance will then lead to self-reaction and inferences. *Self-satisfaction* (or dissatisfaction) refers to the affective state associated with performance, evaluation, and interpretations. People are motivated to reduce the gap between goals and performance, resulting in changed goals or performance (Bandura, 1997). Ultimately, *adaptive or defensive inferences* are made about changes to self-beliefs, goals, or performance approaches. These either direct change or fortify behavior and beliefs. Openness and adaptivity would entail learning from self-regulation and the information obtained to inform future performance. Negative inferences may lower self-beliefs or interest, or lead to intentionally poor strategy selection to defend self-image (i.e., self-handicapping).

2.2.3 Development and Performance Effects of Self-Regulation

While there is a degree of self-regulation in all action, “what distinguishes effective from ineffective forms of self-regulation is instead the quality and quantity of one’s self-regulatory processes” (Zimmerman, 2000, p. 15). Self-regulated learners are self-motivated, creative, and manage their work time well (Bartholomew, 2017). The development of self-regulation leads to more internalized information sources and strategies—in contrast to social comparison (Schunk et al., 2014)—and flexibility to adapt to environmental and personal factors to produce desired outcomes. It follows that self-regulation is positively correlated with other desirable cognitive and affective skills such as self-efficacy (Aurah, Cassady, & McConnell, 2014; Britner & Pajares, 2006) and motivation, interest, and engagement (Guay, Vallerand, & Blanchard, 2000; Honey, Pearson, & Schweingruber, 2014).

Self-regulation is developed through practice, over time. Therefore, toward the aim of empowering student self-sufficiency and lifelong learning, education should seek to improve self-regulation. Adolescents often have weak self-regulatory skills, setting goals poorly and failing to anticipate consequences (Zimmerman & Cleary, 2006). “Weak self-regulators achieve limited self-development” (Bandura, 2006, p. 11). Zimmerman (2000, pp. 26-27) noted that the main dysfunction in self-regulation was relying primarily on reactive methods instead of using forethought and reflection-in-action, proactive techniques, to achieve desired outcomes.

What is an appropriate degree of self-regulation among high-school students? Previous research on self-regulation has spanned children to adults, and from its history in classroom contexts, self-regulation has been of interest for secondary-level researchers. With instruction, high school students have reported an increased capacity for summarizing ideas, critical thinking, metacognition, and learning from peers—all self-regulation strategies (Sungur & Tekkaya, 2006).

2.2.4 Measuring Self-Regulation

Intention to develop self-regulation skills suggests that these skills are perceptible to some degree, and measurable. Measurement is necessary to accurately determine students’ proficiency at monitoring and learning from their circumstances. So then, how is self-regulation itself measured? Given its tacit and abstract nature, self-regulation is difficult to observe and measure (Thorndike & Thorndike-Christ, 2010). Subsequently, disagreement about the definition of self-regulation in practice results in important implications: it needs to be studied contextually and the choice of measurement operationalizes self-regulation for the research (Baker & Cerro, 2000; Winne & Perry, 2000). Winne and Perry (2000) described properties of measuring self-regulation as either an aptitude or an event, in other words, an “enduring attribute” or “discrete chunk” of time. In the later, setting is an important aspect for cueing and interpreting potential self-regulatory actions. Seven methods for measuring self-regulation were then discussed by Winne and Perry (2000). These are organized according to how the method conceived self-regulation and summarized next. The discussion noted some potential overlap, for example, depending on the configuration of interview questions; therefore, I organize each method on a spectrum of aptitude-orientation to event-orientation in Figure 8.

Self-report examples include the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich, Smith, Garcia, & McKeachie, 1991), which uses many questions and Likert-scale responses to measure student self-regulation. Students may respond to questions on study habits or mental faculties when performing a task. Like other questionnaires, these scores are

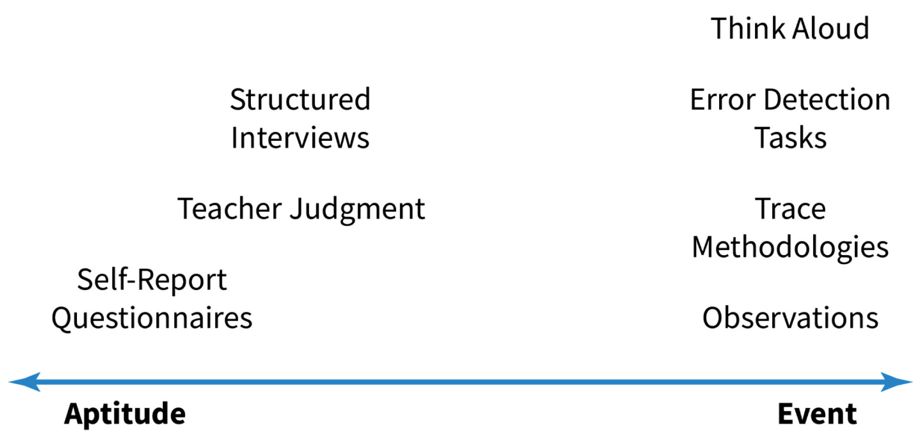

Figure 8. Aptitude-event orientation of protocols to measure self-regulation. Due to flexibility in configuring the protocol, and the information sources used by each approach, there are some instances of overlap.

interpreted according to their alignment with underlying factor theories or aggregated to represent a global level of self-regulated behavior (DeVellis, 2003; Follmer & Sperling, 2018).

Interviews can range in the scope of each question and overall target of the interviews, therefore they fall in between each orientation. However, based on the intention to generalize responses, interviews tend toward aptitude measures. One approach to the analysis of interview questions for self-regulated learning is called microanalysis. This process involves asking directed questions and coding the occurrences of self-regulation strategies (Cleary & Zimmerman, 2001; Follmer & Sperling, 2018).

Next, teachers may be asked to judge students' skills. Because these judgments are based on in-person observations they have a foundation of event-orientation, yet also seek to generalize an estimate of student skill level. For this reason, teacher judgment methodologies are placed toward the aptitude-orientation for measurement of regulated behavior.

Think aloud tasks are used to have students report their self-regulation verbally and have been especially common to investigate self-regulation in reading comprehension (Azevedo, Greene, & Moos, 2007; Winne & Perry, 2000). This information is especially contextualized with "little other standard information" (Winne & Perry, 2000, p. 550), making it event-focused. In think-aloud methodologies, the research participant vocalizes their thinking, from which analysis can extract self-regulated strategy use (Greene, Robertson, & Costa, 2011).

Error detection tasks are observations to see whether students detect mistakes in material and observe their reactions; these are also contextualized, given that the error, surrounding material, and instructions impact the results (Baker & Cerro, 2000; Winne & Perry, 2000). The results of error detection tasks are to understand the perception of students and their reactive strategies for making sense of errors.

Trace methodologies examine the annotations (e.g., highlights, underlines, margin comments) of students, typically when reading, to make inferences about their cognition and regulation. They can also be used to log where attention was spent electronically (Wolters, Benzon, & Arroyo-Giner, 2011). As an indicator of self-regulation, trace methodologies have been used to explain how strategies or resources are regulated, though not why.

Finally, observations have been used to see what learners do within context (Winne & Perry, 2000), showing alignment with other event-oriented measurement approaches. For example, assessment of ongoing performance can be structured about specific self-regulation strategy use, or behavioral cues. An advantage of this type of performance assessment is its basis on performance rather than recollection (Wolters et al., 2011).

Another review of research by Saks and Leijen (2014) similarly noted the use of diverse methods to measure self-regulation, though they commented on the trend toward dynamic means to measure self-regulation in context, including think aloud protocols. In short, an array of methods has been used in research to bound and measure the construct of self-regulation. Measurement of self-regulation should take into account the context and recognize that the chosen methods play a role in the working definition of self-regulation for the research being undertaken.

2.3 Regulated Responses to Failure Framework

Finally, in this section, I articulate similarities between design problem-solving and self-regulation patterns, to make a case for conjoining these domains in this study. While paired components of each theory have been examined previously, the integration of self-regulatory strategies and design has not been undertaken holistically. However, self-regulation strategies are generalizable, and, therefore, applicable to design processes. This argument builds up to a contextualized framework for how responses to design failure might be regulated by beginning designers.

2.3.1 Existing Theoretical Links

While limited instances of research that coupled design and self-regulation were identified, the subcomponents of self-regulation are frequently associated with design cognition. For example, design self-efficacy (Carberry et al., 2010); goal setting, in the form of problem framing (e.g., Dorst, 2011); self-recording, in the form of design documentation (Svarovsky & Shaffer, 2006); or self-evaluation modeling through design critique or decision-making (Schön, 1983; Wendell, Wright, & Paugh, 2017) have been topics of study. Indeed, referring to self-regulation as the intersection of cognitive, metacognitive, and motivational domains, Barak (2010) commented that "fostering metacognition in the technology class has received relatively little attention in the literature on technology education" (p. 393). Taken together, the application of self-regulatory subcomponents to design practice supported the extension of holistically examining self-regulation in design.

Fit for self-regulation theory in this education setting also comes by the use of authentic environment and use of design artifacts and emphasis on iteration as strengths for supporting self-regulation (Barak, 2010). Authentic challenges embed information and can provoke reflection on realistic scenarios (Jackson & Strimel, 2018; Strimel, 2014). One type of artifact, design journals, are evolutionary documents that describe what transpired in the design process; they facilitate planning, management, and reflection in design—all key self-regulation elements (Lin et al., 1999, p. 48; Svarovsky & Shaffer, 2006). Another type of artifact, physical representations or prototypes created in design, embody learning. Examination of artifacts allows learners to examine their own process and identify ways to improve. Furthermore, iterative cycles are found in both design and self-regulation, whereby first performance attempts are built upon to learn and improve (Barak, 2010; Lindgaard & Wesselius, 2017). Feedback from the success or failure of design ideas is an important information source for future learning, and can naturally inform the design process (when handled correctly, as discussed in Section 2.1 Learning from Failure). Therefore, through authenticity and elements in the environment, both design and self-regulation gather information to shape future performance attempts.

Another subcomponent of self-regulation, reflection, has frequently been considered a hallmark of good design (Crismond & Adams, 2012). Purzer, Goldstein, Adams, Xie, and Nourian (2015) argued that learning in design may not be possible without reflection, and connected reflection to "systematic experimenting, scientific explanations, and decisions-making," for greater understanding in design (p. 9). Rowland (2004) also included reflection as a core competency in design by including mindfulness, judgment, and a positive attitude toward error among other ideas. Self-regulation, specifically within a context of problem-based learning such as design, is also a way to foster creative idea development (K. Adams & National Center on Education and the Economy, 2005; Barak, 2010; Kelley & Rayala, 2011).

2.3.2 Example Application from Science Education

For the integration of design and self-regulation theory, a framework provided by Peters-Burton (2018) offers an analogous learning context: it integrated science instruction and self-regulation phases. I describe the formation of that framework prior to presenting the framework of this research study.

The framework began with an illustration of how self-regulatory processes might play out in science-based design activity, an open-ended process with analogies to my case context of soft robot design. Hypothetical descriptions of self-regulation in practice for two students were given—one student with poor self-regulation, the other with skillful self-regulation. On one hand, a student with poor self-regulation might begin a project oriented from the negative experiences of failure in past projects (self-efficacy). Throughout the project, he may jump to work without specific strategies (strategic planning), get distracted (attention focusing), and place blame for poor performance (attributions). On the other hand, a skillful learner might start out with challenging goals (goal setting) and compare her progress to these goals throughout the project (self-monitoring). Whether interested in the task or not, the she can foster value by findings applications for her learning (intrinsic interest). Furthermore, challenges throughout the project are framed as learning opportunities which validate knowledge (adaptivity). Feedback from her teacher and these experiences shapes her strategy selection for future projects (self-evaluation). The beginning step in this framework, these annotated narratives, exemplifies the process for aligning self-regulation subcomponents with the in situ behavior of students that was undertaken in the present case study.

Peters-Burton's (2018) framework highlighted parallels between science teaching and self-regulation subcomponents, and opportunities for science teaching to leverage self-regulation theory. Parallels came from synthesized research on science learning and took the form of explanations for how self-regulation is evidenced in learning. Recommendations emerged from the missing self-regulation theory subcomponents, not evidenced in teaching approaches or learning. The theoretical argument made by Peters-Burton (2018) was instructive for understanding how self-regulation strategies were used by students in the practice of open-ended learning environments and provided further evidence that these strategies can be observed. The interpretation of self-regulation behaviors was likewise adapted to fit beginning designers' strategies for responding to design failure.

2.3.3 Integrated Framework

Based on similarities between self-regulation and design phases, I articulate a framework for regulated responses in design failure (Figure 9). The framework conjoins self-regulatory phases with design phases, and portrays when success or failure is made overt through judgment of performance. Elements of the framework use the language of self-regulation, are characterized similarly, and afford supplementary elaboration based on design contexts. These elements of the framework are described in the next paragraphs.

Three phases of self-regulation are featured, whereby action is planned, carried out, and reflected upon. The three self-regulatory phases are matched to phases in a reduced design process. Several authors have distilled features of design to three basic aspects: analysis, synthesis, and evaluation (Dorst & Cross, 2001; Dubberly, 2004; Jones, 1963). Analysis may be

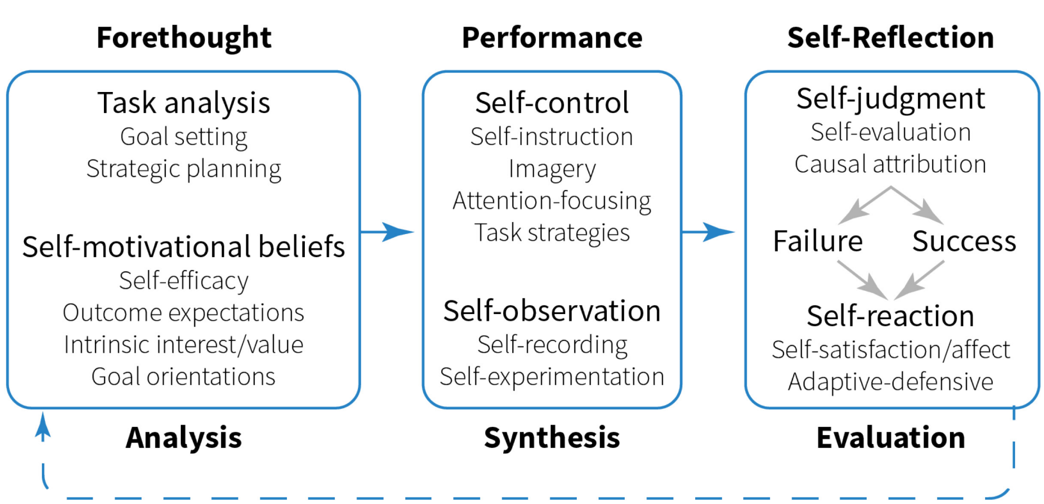

Figure 9. Theoretical framework for regulated responses to failure. Self-regulatory phases (indicated on top) align with design phases (on bottom). Subcomponents of self-regulation are used to process information through each cycle. Success or failure experiences are made overt through judgment of performance and continue to reaction and future cycles of regulation.

thought of as the front-end of design, including stages such as identifying the problem, establishing criteria, and gathering information. I consider it divergent, expanding the problem-space and information available. Synthesis is a convergent phase of design, aimed at processing the information and producing a solution. Based on the design environment, the end-point of design may be a design proposal, prototype, or solution. Nonetheless, to arrive at the solution there are repeated stages of construction and evaluation. Therefore, each phase of iteration in design may be thought of as corresponding to the phases of self-regulation, where information from the previous attempts is assimilated (forethought) to shape the approach (performance) and results are reflected upon (self-reflection) to gauge success of the idea against criteria and determine whether further iterations are needed. Ideally, through subsequent iterations, self-regulation and the designed solution become more sophisticated.

As each round of performance concludes, ideas are tested and evaluated; at this stage of self-reflection, the idea is determined to be a success or failure. What are the criteria for this decision? Criteria are established in earlier thought—forethought and design analysis—and influenced by reflection on performance. Interpretation of the situation leads to further reactions and phases of iteration. The benchmark of an idea to criteria and expectancies is complex and may play out in a variety of ways. Two hypothetical situations are described and annotated based on the subcomponents of self-regulation evidenced.

1. A student having high expectations (outcome expectations) and confidence (self-efficacy) may perform well. Despite the idea working to meet the design criteria (goal setting), it failed to meet the student's expectations (self-evaluation). The student reflects on the design experience and determines that modifications to the design (causal attribution) may lead to success (adaptive). The student repeats the process, hoping for better results.
2. A student with low expectations (outcome expectations) is not very interested in the project (intrinsic interest). In fact, the only reason they are working is to get it done (goal orientations). During the project they exhibit little attention to what is being done (self-recording) and when their idea does not work (self-evaluation) they are not worried (self-satisfaction). They just document some changes to make and move on to the next assignment.

Despite having the same evaluation, the idea did not work, the interpretation and ramifications for future performance are different, in part because of regulating forethought. Judgment of success or failure, having been framed by forethought, then catalyzes reaction such as choosing to revise the performance or accepting satisfaction.

This framework represents the lens whereby I examine self-regulation of beginning designers, described in Chapter 3. Without making claims as to the efficacy of self-regulation or the positivity or negativity of strategy approaches or reactions, the chronology of students' design processes were observed and annotated according to the elements in Table 2 and Figure 9. By doing so, this study can describe patterns of self-regulation in a design context, with specific attention given to evaluations of failure or success.

2.4 Summary

Previous research in design learning has promoted the opportunity to plan experimentation and learn from failure in iterative cycles. Design has unique conceptions of failure that may support reflection and growth as a result of failure experiences. A systematized review of articles related to learning from failure identified several catalysts—failure uncovers key concepts and provokes thoughtfulness and reflection—and conditions—positive climate and communication—for successful growth from failure. However, a dearth of articles in technology education, studying the design experience in-depth, and recommendations to further investigate how self-regulation informs iteration and learning in design, support the worth of this case study investigation in broadening understanding.

Self-regulation theory is ostensibly a good framework to continue this investigation of design reasoning. I have described self-regulation theory and its subcomponents, which lead to well-reasoned performance. Measurement strategies of self-regulation events are contextualized, playing to the strengths of this case research. Furthermore, I have described conceptual similarities between the iterative cycles of design and self-regulation, leading to a theoretical framework for regulated responses to design failure. In the next chapter I describe my approaches to investigate and interpret failure in the design process.

CHAPTER 3. METHODS

Congruent with the interest in uncovering student experiences and self-regulatory strategy use related to failure while designing and developing an understanding of these experiences, this research utilized a case study approach. The intended approach was also situated at the confluence of three research needs (exploring impacts of student confidence, emergent self-regulatory practices, and interactional dynamics during problem-solving) identified by reviewing existing literature on learning from failure. The methodology also draws on the framework for regulated responses to design failure described in Chapter 2.

This chapter describes the pragmatic paradigm which informed this work and elaborates on my positionality and how it might impact my interpretations of the case. Next, the setting, participants, and information sources are described. Collectively, these elements are important for the instrumental aspect of this case study—these are the means whereby I build understanding of the practices of beginning designers. To make sense of the experiences, data analysis and interpretation approaches are described. Finally, approaches to ensure research validity, reliability, and trustworthiness are given.

3.1 Pragmatic Philosophy

In order to address questions related to student reactions to failure, the research necessarily targeted contextual and experiential aspects. As described in the regulated responses to design failure framework, self-regulation and design decision-making are both framed in past information and experience. The combination of framing, failure or success experiences, and interpretations, then shape future iterations. Therefore, the guiding questions pertain to the "what" and "how" of students' encounters with failure and enacting self-regulation strategies. The primary guiding question for this study was, "How do beginning designers use self-regulation when navigating failure and iteration?"

Qualitative work was necessary to explore the experiences of students, as well as corroborate information sources to describe the design context and iterative pathways of student participants. The qualitative tradition of case study research was chosen for this task because it uses multiple perspectives to produce "concrete, context-dependent knowledge" (Flyvbjerg, 2006, p. 223) which can be applied to the development of expertise. More specifically, I conducted an instrumental case study with nested groups[2] using multiple participating teams. Using teams, nested in the larger context of the soft robot design experience, affords investigation within a team, between different teams, or across all teams (Baxter & Jack, 2008). Furthermore, while multiple perspectives are contrasted to build understanding of the wider case, the nested case approach also recognizes and credits that the students' experiences "occur in a wider, connected context" (Gary Thomas, 2011, p. 155). Nested studies can focus inquiry, however analysis also needs to return to broader case (Yin, 2014, p. 55), described through integrative analysis across cases. Given the fairly consistent implementation of the soft robot lesson among classrooms from the same partnering district, I maintain that my focus was on the broader case of student design experiences and strategies, tying findings to the interplay between self-regulation and failure.

Consequently, my approaches changed to fit the needs of the inquiry. The guiding questions of this study and my interest in how students learn from failure have turned me from my traditional application of quantitative research (e.g., Jackson, 2018; Jackson, Mentzer, & Kramer-Bottiglio, 2018; Jackson, Mentzer, Laux, Sears, & Asunda, 2016; Jackson, Mentzer, Zhang, & Kramer, 2017) to conduct a case study. This turn of method is one demonstration of the pragmatic worldview taken for this research. Creswell and Poth (2017) note another characteristic of pragmatism, which aligns with case study methods described hereafter, using "multiple methods of data collection to best answer the research question" (p. 27). And regarding analysis, Onwuegbuzie and Leech (2005) promoted "methodological pluralism" (p. 381) and described the opportunity in pragmatic research to "combine macro and micro levels of a research issue" (p. 383). In my view, the two analysis approaches described in this chapter offer complementary representations, at a macro and micro level, of what was experienced in the case. I acknowledge that my interpretation of these experiences is not necessarily the conception of the participating students. Rather, the interpretation is chosen for its utility in explaining outcomes and clarifying conceptions (Cherryholmes, 1992), and its fit with theory informing this work.

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[2] The terminology of case study is varied. Gary Thomas (2011) uses the term "nested," Yin (2014) calls these "embedded," while Stake (1995) calls it "collective case study."

3.2 Context Development and Positionality

My attention and interpretation in this research was influenced by my past experience with the soft robot design curriculum context. This case study is situated in a larger research project that I have been involved in since its early stages. Early phases of the research involved developing the fabrication process and lesson plans; I contributed to both aims by modeling and prototyping fabrication materials on the one hand, and outlining and drafting lesson materials on the other. Before my time observing the lessons completely (the second year of implementation for these teachers), I had also 1) made my own soft robot grippers, 2) conducted pilot teaching experiences, 3) delivered materials in professional development trainings to participating teachers, 4) shared the plans and materials at research and practitioner conferences, 5) observed the low success rate of final grippers, 6) heard teacher reflections and modifications to the materials (based on their first implementation attempts), and 7) analyzed participating student self-efficacy, motivation, and interest responses after participating in the design experience (in the first implementation attempts; Jackson et al., 2018). Suffice to say, I was heavily involved in the development of the soft robot design experience up to the point that this case observation was conducted.

Yet, while I was intrinsically motivated to study this context to seek to understand it, I assert that it offers a lens whereby self-regulation strategies and strategies for navigating failure can be observed. As discussed in section 1.3 Case Context, the soft robot design experience necessarily involves iteration through repeated phases of fabrication. Students construct and test soft robot fingers multiple times and then construct a completed gripper design to address the design challenge. Furthermore, my involvement in the development of these materials affirmed that failure was embedded in this design experience.

My experience as an instructional designer for this curriculum, specifically, and as an educator, generally, also shaped my interactions with students while conducting this research. The contributions of this project align with my aspirations for fostering designerly ways of thinking, including self-regulated action in the face of failure. The design experience was established to be challenging, requiring students to try multiple times and make informed decisions in their design-process to succeed. Despite this intention, I found myself questioning whether failures in design were a function of low-tolerance in the fabrication process, a limited number of iterations (i.e., given more time would there be more success), or lack of understanding and learning regarding soft robot design. I also found myself asking whether the level of success was good, or good enough, and to what degree students should be scaffolded toward success in design. However, when visiting with students I tried to set these aspirations and questions aside to focus on the experience, as enacted in the classroom. In visiting with students, I positioned myself as an instructional designer for the lessons, hoping to understand what it was like for students. My interaction with the students was friendly—without questioning their actions or understanding as a teacher might—and related to the research at hand. For example, I answered personal questions (e.g., I told the students that this research was part of my graduate school requirements) but not content questions (e.g., I did not explain why a failure occurred even if I knew the answer) and I occasionally reminded students to speak aloud. In one instance I reminded students they could let the silicone cure overnight in a mold; forgetting this option, their alternative was going to be to quit early for the day and waste time near the end of class and begin once more the next day. While the reminder brought up past information, it also bypassed lost opportunity for observation by allowing students to continue their design work up to the end of the period. These interactions fit my pragmatic approach to research by seeking to best answer the research question without influencing the experience or students' natural self-regulation in design, and retaining expediency in doing so.

3.3 Case Setting and Participants

Building on the successive iteration and improvement of the experience after one year of familiarity by the teachers, this research was situated in the second classroom implementation of the soft robotics material. Four student pairs, in two classrooms, represent the nested units of analysis for this study. Many levels—the district, teacher and classroom, and student—are important for contextualizing this research.

The District and Course: The participating district is located in Maryland, with a mix of rural and suburban areas. The two school sites located therein are public schools for grades 9 to 12. The two classes observed were teaching an introductory technology and engineering course, intended for 9th grade students. The standards-based course, called *Foundations of Technology*, was intended to help students understand and apply technological concepts in authentic situations (International Technology & Engineering Educators Association, 2017). The course uses a mixture of group and individual activities in design and problem-solving. In the participating district, the *Foundations of Technology* course was required for students.

The Teachers and Classrooms: Two participating teachers were identified as part of the broader soft robotics study. They were chosen for their past participation in the research project, therefore, familiarity with the design context, and willingness to host the in-class observations and research for this case study. Both teachers had been involved in the first implementation of the soft robot lessons and adaptation of the material to its current state. Each teacher had been teaching for over 10 years. Though teachers were aware of the case study, and helped select the design teams to observe, they were instructed to interact with teams as normal.

The classroom climates maintained by the two teachers had similarities and differences, though both would be recognized as traditional technology and engineering classrooms. Mr. Gray (all names are pseudonyms) began the soft robot design lessons in a classroom and moved to a nearby lab space as students transitioned to the hands-on, fabrication stage of the design activity (Figure 10). A subtle message of this shift in location may be to reinforce the hands-on nature of the lesson to students. A wall in the classroom was covered in motivational quotes. Students also had a familiar routine to retrieve and store their design documentation in bins near the back of the classroom. This storage spot was also home to other resources such as past assignment instructions and sheets describing steps in the design process. Daily introductions took place positioned toward the projector screen, with a question for students to answer, class-wide conversation on the topic, and then a teacher-led a briefing on the day's objectives. The complementary lab space offered more freedom of movement—supplies were stored on a central table and students were free to find a work place, and move to get supplies or cure their soft robot parts. The class was fairly autonomous following the introduction of objectives; the teacher monitored student progress and was available to answer questions.

The classroom space of Mrs. Childs seemed oriented toward group work—with large tables for student seating, all quite close together—and illustrating examples of the learning process—the other half the room included shelves for books and project storage (Figure 11). Students worked in the same location throughout the project. The design lessons began with thorough instruction related to the scientific principles and fabrication process undergirding soft robot design. Mrs. Child's involvement throughout the lessons included a check-in at the

Figure 10. Photographs of Mr. Gray’s classroom and lab space. Instruction began in the classroom space with assigned seating and orientation toward the daily warmup question (top). Two images of the lab space, left-facing (middle) and right-facing (bottom) show work tables and supplies.

Figure 11. Photograph of Mrs. Childs's classroom space. Work tables (foreground) were assigned seating. Shelves (background) were for project and tool storage. A counter at the front of the room held supplies, with the projector screen as a backdrop (out of image to right).

beginning and end of each class, as well as monitoring progress by moving through the class during the lessons.

A last aspect which contextualized the design experience I observed was the fidelity of implementation of the soft robot lessons. In other words, the lesson delivery in practice was shaped by these teachers' professional judgments and adaptations of the soft robot lesson plans lead to the formation a unique experience. Three characteristics of the lesson implementation were observed and expected to influence interpretation of the results. In reporting the results, I attend to these changes of approach and their potential for impacting students' design experience.

First, contrary to my expectations, both teachers reviewed soft robot fabrication steps by showing a demonstration video, and passing out instruction sheets with further details. Although they later demonstrated the process, these external resources were featured prominently in instruction. Furthermore, students were encouraged to return to these resources first when asking questions of the teacher. In analysis, these resources became key reference points in the design process. Despite the provided fabrication instructions, students were still required to plan their fabrication process, consistent with the conceptualization of design in this research (encompassing conceptual and process design). They could determine how to use and adapt fabrication steps in each cycle of design, rather than following rote procedures.

Second, teachers were consistent in using repeated phases of fabrication, and let students know in advance that their purpose was to design and experiment and uncover insights, before producing a final soft robotic gripper design. Some elements of iteration were prefigured, and assigned for students. In the case of Mr. Gray, students had to brainstorm several ideas, then proceeded to test all of these ideas simultaneously. For students in Mrs. Child's class, distinct phases were required: make a first soft robotic finger and test it; make a second soft robotic finger and test it; and make a third finger for testing before moving on to make a complete gripper. Though there were differences in patterns for iteration, in both cases students were encouraged to learn from their first ideas to improve both their fabrication process and their design. It was also apparent that students would transition from iteration in finger designs to gripper designs. However, after the necessary attempts (several fingers and one gripper), the decision for iteration was open-ended. Both teachers had ample time at the end of the lessons for students to attempt an additional gripper design—due to unsuccessful gripper fabrication, this option was usually taken by students.

Third, a final difference of note was related to beginning of collaborative work by the students. Mr. Gray indicated that, based on past success in encouraging individual contributions, students began the design process individually before meeting as a team to decide upon ideas and move forward. As a result, the first days of design work, and my observations, was of students working individually, or with neighbors with whom they would not necessarily continue working. In contrast, Mrs. Childs paired students from the beginning of the design challenge and they were expected to work together through the duration of the project. Differences in structure for team cooperation may yield slightly different patterns in team dialog; based on the timing of team formation, the first tasks as a team are different. For example, individually developing ideas, the first task of teams in Mr. Gray's class was to share ideas, evaluate them, and make a decision. When beginning to design together, a team may open by discussing the design challenge and requirements, then co-developing ideas. While the implementation in each classroom was slightly different, these design lessons were taught in the tradition of each classroom and were familiar to students.

The Students: As mentioned, I observed four teams (eight students) in their soft robot design process. The lesson is based on student pairs. In case study research, and in selecting teams, there is not an intention to form a representative sample or even include all possible characteristics of student teams (Gary Thomas, 2011). The foremost criteria for student selection was parent and individual consent to be audio recorded during the research. Next, van Someren, Barnard, and Sandberg (1994) recommend two considerations: 1) the cooperativeness of the participant and 2) the participants' verbalization skill. For these reasons, teachers' knowledge of their students was used to purposively select student teams to "maximize what we can learn" (Stake, 1995, p. 4). This included asking for variety among the teams, those that might approach the problem from different ways, or be made up of different types of students. Analysis of the data from four teams is an appropriate sample to afford thematic analysis within and across teams (Creswell & Poth, 2017, p. 160) as well as sufficient certainty regarding beginning designer patterns of self-regulation (Yin, 2014, p. 61).

According to the teachers, teams were recommended for being willing to work with the researcher. All participants were White. The genders and motivational profiles for each participating student are presented in Table 3. Since beginning conceptions shape future thought, the team members' self-efficacy, motivation, and interest were considered using data available as part of the larger curriculum efficacy investigation (Jackson et al., 2018). Though tentative, the levels of self-efficacy, motivation, and interest following the lessons may also be indicative of the experience, by way of self-judgment and self-reaction in the operational framework. Differences between the student response and the classroom distribution are indicated with the direction of deviation, based on a z-test with $p < .05$ for each measure. Most of the designers observed had a typical response, relative to their classes, for the questionnaires used. However, Sydney reported lower motivation than the rest of her class before the lessons, which increased to average; Evan reported higher amotivation after the lessons and his interest dropped more than the usual variation among the class; and Wes reported higher motivation after the lessons than his class did, though his interest was typical.

Table 3. *Design Team Demographics and Motivational Characteristics.*

Teacher	Team Members	Gender	Motivational Characteristics
Mr. Gray	Sydney + Jordyn	female female	Beginning motivation (–) Typical response
Mr. Gray	Evan + Fiona	male female	Ending amotivation (+) Typical response
Mrs. Childs	Brynn + Katelyn	female female	Typical response Typical response
Mrs. Childs	Wes + Taylor	male female	Ending motivation (+) Typical response

Additional bounds on the case, as described in Chapter 1, were based on the implementation of the soft robot lessons. These included the timing of the soft robot lesson and the nature of instruction and the nature of assessment. The lessons were conducted in the latter half of the introductory course for approximately five meetings; instruction was design- and team-based, with the anticipation of iteration and the production of artifacts; and assessment was based on the production of artifacts, specifically a design journal, gripper design, and presentation. Collectively, these cues informed student behavior seen in person.

3.4 Information Sources

Several information sources from the design process, alluded to by the bounds of the case, were reviewed together to represent the design experience. Recognizing that students' experiences can be best captured while they work, I employed observations and field notes and audio recordings of the design process in action. This data stream captured students planning, work, and reflection as occurrences of failure or success took place, aligned with the self-regulatory and design phases described in the regulated responses to failure framework. Next, design journals and artifacts were collected as evidence documenting the experience. Finally, after the design experience, I conducted follow-up interviews with the design teams to verify my notes and representation of their design work, especially judgment regarding success and failure. Observations and audio recordings represent the chief information source which will be used to address the research questions under study. The specific procedures supporting the use of these information sources are each described.

3.4.1 Observations and Audio Recordings

Wolcott (2005) asked, "Can whatever [you] want to study be 'seen' by a participant observer at all?" and "[Are you] well positioned to observe those phenomena?" (p. 88). Observations and field notes as a "nonparticipant" (Creswell & Poth, 2017, p. 168), complimented by audio recordings to capture the experience, are appropriate to elicit the "what" of the experience, the concrete details, the movement through the design process and how failure was encountered. At the beginning of the observations, I introduced participating students to the general purpose of the research (to inform teaching), showed them the recording equipment, and invited students to think aloud as they worked (see Appendix D), telling them that I would also be moving around the classroom to observe. In order to observe students' natural strategies and reactions for failure, I did not ask reflective questions of students while working. My presence led to occasional questions about the lesson content—which I answered with an ambiguous question, "What do you think?"—or my identity or role as the researcher—which I answered as authentically as possible. Throughout the observations I interfered as little as possible (van Someren et al., 1994, p. 41), mainly prompting students to say what they are thinking when working if they remained quiet.

Think-aloud protocols are commonly used to make manifest the thinking of research participants. They have been used in design research to understand design processes and actions (e.g., Atman, Chimka, Bursic, & Nachtmann, 1999; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Dorst & Cross, 2001; Mentzer, Becker, & Sutton, 2015). They have also been used in studying self-regulation (Baker & Cerro, 2000; Winne & Perry, 2000). And these procedures have been used for both individual- and team-based analysis, where it was argued that thinking aloud and team conversation offered similar insight into thinking (Goldschmidt, 1995). Compared to retrospective interviews, where accounts may be incomplete or incongruent with work in practice, having participants think aloud while working comes "much closer to representing thought processes" (Goldschmidt, 2014, p. 27). And compared to analysis of design products alone, verbalization of thinking offers insight into design reasoning and strategy use (van Someren et al., 1994, p. 4).

A few concerns exist regarding the validity of think-aloud data. These concerns specifically question whether the act of thinking aloud modifies action. Evidence comparing various thinking aloud tasks to typical work showed that merely stating thinking does not extend the time to complete tasks and had little effect on the mental workload required. Therefore, care should be taken to have participants state their thinking, rather than evaluate or offer assessment, because those interruptions do seem to affect performance (Hertzum, Hansen, & Andersen, 2009). However, design requires reflection-in-action (Schön, 1983) and the planned structure for capturing design processes was not substantially different from the status quo, partly alleviating these concerns. For instance, design naturally requires successive divergent and convergent (evaluative) processes therefore any assessment and evaluative thinking done by students would naturally emerge. Furthermore, students were working in pairs for the lessons, whether or not they participated in the research project, requiring natural communication of thinking

(Goldschmidt, 2014; van Someren et al., 1994). These dialogues can lead to natural explanation and justification, for example, when resolving differences of opinion of making decisions (Wendell et al., 2017). The natural flow of collaboration also lessened interruptions in the cognitive processes of problem-solving. Another potential limitation of using think-aloud data in this case was the inability to practice think-aloud procedures with students before starting the lesson, without causing delay for the class; however, because the soft robot designing was team-based, students organically began sharing their thinking aloud.

In my field notes I wrote both "descriptive and reflective notes" (Creswell & Poth, 2017, p. 168). These notes 1) detailed the designers' actions, such as the design processes they were working on or features of the robot they were referencing, 2) described test results, and 3) included asides related to my interpretation or my reflexivity as a researcher—what I was thinking about or feeling. Despite the relative proximity of each design team, I was required to shift my focus back and forth; teams were not operating in parallel during the fabrication process, therefore transitions in the process (e.g., while the silicone was curing) provided a natural time to migrate. In-person observations took place for the first week of the soft robot lesson, five days of class. One class did not finish, therefore observations were conducted by video conference for one and a half days more as teams finished building their soft grippers. However, in both settings I was able to observe work and students were audio recorded. Field notes were initially hand-written; immediately after the observations in each classroom these were digitized and summarized.

3.4.2 Design Artifacts

Students were required to keep a design journal that documented their work, indicated by the assessment procedures of the course. The course plans used a systematic design process including steps of Define the Problem, Brainstorm Possible Solutions, Research Ideas and Explore Possibilities (with citations), Specify Constraints and Identify Criteria, Consider Alternative Solutions, Select an Approach, Develop a Written Design Proposal, Sketch the Final Design, Make a Model/Prototype, Test and Evaluate, Refine/Improve, Create/Make Product, and Communicate Results. These phases of design are consistent with the reduced steps of design referred to in the regulated responses to failure framework. Given the timing of this lesson, in the second half of the course, students were familiar with this process of design documentation;

some even referred to past projects to capture all of the steps. The design journal provided an overview of the design process as it transpired. However, it was also a maturing record, which changed throughout the design process. To capture the chronological development of the design journals I took pictures of the design journals at the end of each workday. Information recorded in the design journals supported the account of the experience and was meant to include evidence of forethought and planning, performance testing, judgments of failure or success, descriptions of iteration and so on, adding meaning to the experience. Yin (2014) relatedly stated "the most important use of documents is to corroborate and augment evidence from other sources" (p. 107).

Additional design artifacts and student work, including soft robot solution attempts, were photographed and kept to illustrate key events of success and failure in the design process. These physical artifacts are a demonstration of the design process: prototyped soft robot fingers or grippers are representative of performance/synthesis phases of design and an embodiment of success or failure. These artifacts, and evaluations, are also described in the design journal and team dialog. Consequently, having these artifacts to handle and describe informed my understanding of the fullness of the experience, which is passed on to the reader.

3.4.3 Follow-up Interviews

About two weeks after the soft robot design lessons concluded, student teams were interviewed by video conference with two aims in mind: 1) to corroborate my account of the experience, in other words to verify my interpretation of events, and 2) to uncover additional information related to design acts that was not directly observed, such as by having students rearticulate or elaborate on aspects of their design process self-regulation. Semi-structured interviews were conducted by video conference with the two teams in each classroom participating together (see Appendix F); interviews lasted approximately 20 minutes. The interview began by asking about their design experience generally, and approaches during the design process—the inception of design, thinking while designing, and reaction to test results were discussed. Students were also asked what they believed led to the success or failure of their design. Finally, the interview concluded by sharing an account of the design process—discussing each sequential design version—and asking teams whether or not the designs were successful, as well as to confirm or add additional detail to the account. While discussing the design process, images of the design artifacts were provided for reference.

3.4.4 Information Preparation

Original data acquired through the research project had various forms, including audio, images, physical objects, and documents. The wealth of information sources used to describe this case is described in Table 4, which divides various stages of preparation. In preparation for data analysis, the individual, daily audio recordings of each student were synchronized and merged within design teams using team dialog or other chronological indicators that had been picked up on the individual recordings (e.g., school bells or teacher instructions). The merged audio recording was culled into a condensed version based on moments when the team was conducting design work. Most of the time this was team discourse related to the design task; at other times this included conversation with the teacher, neighbors, or individual reflection. By focusing only on the on-task moments of team dialog, the analysis does not permit inference about the attention-focusing strategies used by designers. In other words, the stimuli for attention or inattention were confounded by the extraction process. However, this process condensed the self-regulatory actions of designers and accelerated analysis. Once each team's sequence of recordings was condensed, it was transcribed.

Images of the workspaces, design artifacts, and design journals were also compiled to summarize the experiences and ease analysis. Photographs of design artifacts were ordered chronologically and described according to their design variables and any performance deficiencies. This provided a short summary of milestones in the design process that could signal back to incidents of design performance, tests, evaluation, and reaction (in the regulation framework). Finally, daily snapshots of the design journals were compared to one another and the finished version. Then, the finished state of design journals was annotated based on the successive sections that had been added during the process. Similar to the summary of design iterations, this offered insight into the daily efforts of the designers. The journals included evidence of goal setting and planning, as well as evaluation and attributions (through written explanations). However, as a whole, the journals specifically provided evidence of how the designers self-recorded their performance.

Table 4. *Summary of Information Source Quantities.*

Design Team	Observations				Design Journal Pages[c]	Follow-up	
	Days[a]	Full[b]	Edited	Transcript		Interview	Transcript
Sydney + Jordyn	5	6:13:27	3:09:54	99 pages 32,336 words	12	0:17:55	5 pages 1970 words
Evan + Fiona	5	5:42:31	2:08:23	85 pages 22,898 words	11		
Brynn + Katelyn	6	6:06:32	2:43:45	89 pages 24,773 words	6	0:18:21	6 pages 1969 words
Wes + Taylor	6	6:38:06	4:06:04	94 pages 25,860 words	8		

Note: All times are recorded as H:MM:SS. Transcript metrics are in the form Pages (Words)
[a] Observations in Mrs. Childs's classroom were conducted for a first day of instruction, prefacing the design process, and throughout design work. Only the design process days were recorded.
[b] Full recording time was calculated by totaling the maximum recording length of either team member, per day.
[c] Design journal pages is the combined page count of each students' journal.

3.5 Data Analysis and Interpretation

Compared to previous quantitative analysis of the soft robot experience, and other investigations of design failure, a strength of this study is the holistic consideration of the design experience. This broad consideration of the experience spanned students' forethought, performance, and self-reflection through the design process. In line with the case study approach, this holistic perspective was afforded by matching the data from multiple information sources for analysis, as well as conducting multiple layers of analysis. Data were examined in several ways in the analytical process, each described next. These approaches correspond to the macro and micro levels of analysis in pragmatism (Onwuegbuzie & Leech, 2005) and are complementary. First, a synopsis of each team's iterative attempts was made. Second, based on contrasts of observed and self-reported success and failure in the design experience, the process of two design teams was represented with linkography. Linkography offers an overall lens into the connectedness of the design process, for instance, self-regulatory occurrences of planning ahead and reflective thinking. I extend existing linkography approaches by overlaying occurrences of design tests and their results—failure or success. Yet, linkographic analysis was labor intensive (Goldschmidt & Tatsa, 2005). Therefore, selecting two teams for closer analysis fits with the nested case study approach to illustrate complexities of experiences, while still speaking to the focal issue of self-regulation in design success and failure (Gary Thomas, 2011), and was a pragmatic choice. The process of these teams was used to identify patterns of self-regulated response through different sequences of success or failure. Third, typological thematic analysis was used to focus on the specifics of the experience and self-regulation practices. Together, the information sources and analytical approaches, as described, align with the research direction to build understanding of beginning designers' self-regulation strategies.

3.5.1 Marking Success and Failure

Among the four design teams, varying patterns of success and failure emerged from the classroom observations and compiled summaries of design artifacts. To generate an outline of each team's iteration, success, and failure, the dialog of each team was scanned in parallel with photography of successive design artifacts. These photographs represent milestones in the design process, though each photograph may encompass multiple attempts in the case of repairs or troubleshooting the idea. Design attempts were defined to include all soft robot objects fabricated toward the final solution, including soft robot fingers or grippers that were tested, and each subsequent repair attempt. These attempts were identified and marked according to the day they began; the outcomes of each attempt were also marked according to students' judgment, as expressed in the follow-up interviews, and the day of occurrence in the design process. Adapting terminology from Sleezer et al. (2016), attempts could be characterized as a success, a mitigated success (i.e., partly successful), or a failure based on design's performance and the forethought applied (see Appendix G). Abandoned ideas for which fabrication had begun were also included at attempts with the initial start date leading to a judgment of failure when the designers moved on. My interpretation of these experiences, coupled with students' restatement of design success and failure in the follow-up interview introduced contrasts that were used to select focal teams for representation when conducting linkography.

3.5.2 Linkography

Upon selecting two teams with diverse pathways of success and failure, the interconnected design process was visualized using linkography (Goldschmidt, 2014). Forming the visualization was supported by transcripts of the design process, daily design journal notes, and photographs of the design artifacts. Linkography portrays connections in the design process visually (Figure 12), and includes methods to characterize them quantitatively and qualitatively. Compared to other design research methods, it focuses on process rather than categorization of design thinking activities. Linkography is based on the chronological sequence of *design moves*, "a step in the process that changes the situation…. a step, an act, an operation, that transforms the design situation somewhat relative to the state it was in before that move" (Goldschmidt, 2014, p. 42). Next, the *links* between moves were articulated.

Collectively, the moves and links are a linkograph, which can be described quantitatively and qualitatively. For example, the identification of design moves and links was used to show how interconnected the design process was, through the ratio of links to moves, called the *link index*. The link index metric provided an indication of how integrated the design process was (Goldschmidt, 1995, 2014; Goldschmidt & Weil, 1998). Examining links forward and backward in the design process indicated where students were planning and diverging or reflecting and converging (Goldschmidt, 2016). The identification of linchpin steps in the design process, called *critical moves*, was based on moves connected to many others. The identification of critical moves in linkography has corresponded to the findings of other types of process

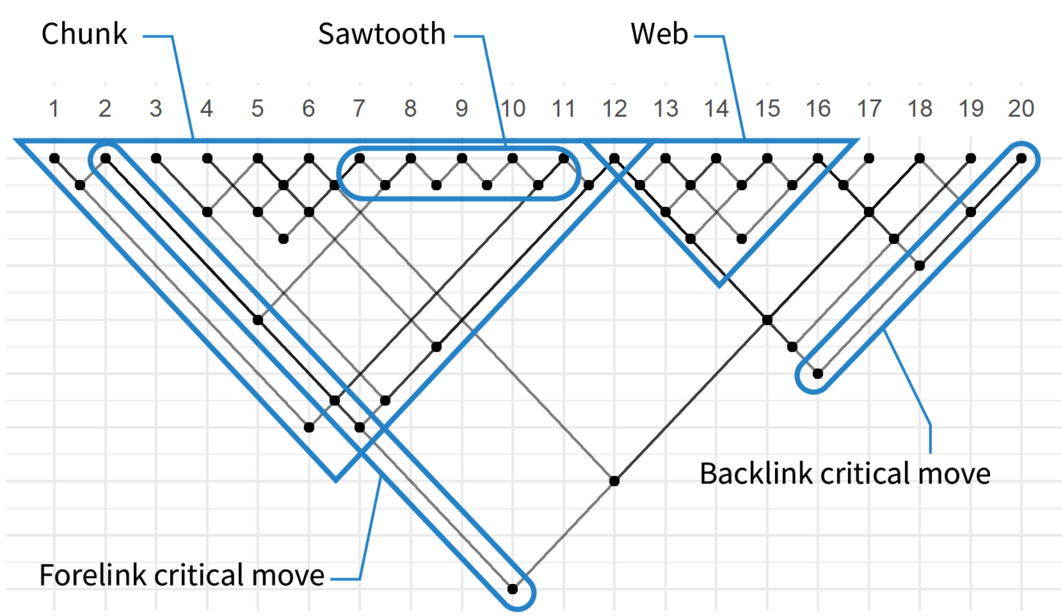


Figure 12. Example linkograph showing common features. Using terminology based on Goldschmidt (2014), this diagram shows a hypothetical linkograph with chunk, web, and sawtooth patterns. A forelink critical move and backlink critical move are also shown.

assessment and suggests the creativity and usefulness of that design step for “thrust” in the design process (Goldschmidt & Tatsa, 2005, p. 595).

Among qualitative descriptors of the linkograph are features such as *chunks*, *webs*, or *sawtooth* patterns (depicted in Figure 12). Chunks are distinct clusters in the arrangement of moves and links, with little overlap. Chunks show efficient “cycles of thought” with a beginning, conclusion, and pivot to the next sequence of thinking (Hatcher et al., 2018, p. 129). A web is a collection of densely linked moves and may signify a brief, intensive passage in the design process to reach consensus or build up ideas (Goldschmidt, 2014). A sawtooth is a sequence of at least four ideas connected in a linear fashion, that do not broaden or synthesize the design-space (Goldschmidt, 2014); referring to the regulated design framework, such a pattern would indicate reactive performance steps—without intentional planning or reflection.

Linkography has been used in a number of settings to make sense of the complexity of the design process. Examples include investigating the formation and creativity of ideas in individual and team design processes (Goldschmidt, 1995); evolution of design ideas in brainstorming (Cai, Do, & Zimring, 2010; van der Lugt, 2000, 2003); design direction in an interactive product design task (Hsieh & Chang, 2017); creativity of design ideas in an educational setting (Goldschmidt & Tatsa, 2005); and team conversations (Kan & Gero, 2004). Linkographic methods are also flexible (Kan & Gero, 2008); several researchers have built additional layers on the sequence of design moves and links. In so doing, researchers have been able to categorize types of moves of links—for example, the type of transformation in idea generation (Cai et al., 2010; van der Lugt, 2000), or whether conversation was related to planning or content (Kan & Gero, 2004)—and further characterize the design process or verify hypotheses. The addition of success and failure occurrences, is one way I add richness to the linkography methods and visualization in this study. Next, I describe the process for arriving at the representation by defining design moves and links and give an example from transcribed dialog.

3.5.2.1 Contextual Application of Linkography

The first analytical pass through the transcript was to identify the moves of each team. This definition of design moves was established based on previous examples of linkography research and recorded in a codebook (Appendix G). Due to the challenges of inter-rater reliability for segmenting design moves (Perry & Krippendorff, 2013), I identified moves using conceptual summaries of the design process as it fit the definition of a design move. Developments in the design process were summarized and put in order to create the sequence of design moves. As a result, and like previous research, the inferred design moves are chronologically fit, though not aligned word for word, with the team dialog (Goldschmidt, 2014, p. 30). My consistency in applying these codebook criteria when reviewing the transcript was also important for preparing robust linkographic results:

- A design move is “a step, an act, an operation, that transforms design situation” that can vary in duration (Goldschmidt, 2014, p. 42).
- The design move may be an idea, a specification, a question, knowledge, or a comment related to the design (Hatcher et al., 2018, pp. 134-135).
- Through these terms, movement to a new idea (lateral transformation) or elaboration on the same idea (vertical transformation) both constitute moves (Cai et al., 2010).
- Finally, consensus building by the designers was also identified as a move because it demonstrated a shift in the state of design. Though the dialog was a restatement of a previous idea, and may not seem progressive, in the team-based design context these types of comments move the design session forward by unifying understanding of and commitment to the design. In the case of prolonged back-and-forth to build consensus on one element of the design, a single design move was used for the exchange.

Next, links were formed based on the contents of design moves by asking, “Is there a link?’ for every pair of moves in a sequence (Goldschmidt, 2014, p. 48). Links were determined on the basis of common sense, relying of my familiarity with the design context and interpretation of students’ dialog (Goldschmidt & Weil, 1998, p. 90). Here, also, guidelines in previous linkographic studies and in the codebook were useful for denoting link examples:

- Direct references to previous design moves constitute a link to the present design move.
- Idea supplements or modifications or tangents are coded with a link to the previous idea (van der Lugt, 2000, p. 518).
- Ideas within the same “chain of thought” are linked (Hatcher et al., 2018, p. 136).
- Moves are linked to the initial source, not necessarily each connected move unless a new element provided the connection.

Using the text of the transcript and corroborating evidence, two types of links were formed—backlinks, when a connection was made backwards in time (e.g., in reflection), and forelinks, a connection made forward in time (e.g., from planning; see Figure 12). For illustration, a section of design dialog is provided in Table 5, with the transcript, conceptual design moves, and links. Moreover, a description of the codes used, with examples and further elaboration is included in Appendix G.

A final extension of the visualization was to overlay design judgments on the linkograph, and whether ideas were successful or partly successful or unsuccessful, as milestones through the design experience. Others have similarly overlaid characteristics of the design process or categorized different types of links on a linkographic representation to inform interpretation (Hatcher et al., 2018; van der Lugt, 2000).

3.5.3 Typological Analysis

Following closer inquiry of two teams, provided by linkography with the conception of success and failure equating to design attempts, I applied typological analysis, an analytical approach based on the division of data to predetermined typologies (Hatch, 2002), to characterize the design processes and self-regulation strategies of the beginning designers. An overview of qualitative analysis processes by Creswell and Poth (2017) noted the common pattern of preparing data, coding segments, and producing themes from a combination of codes. Indeed, Gary Thomas (2011) described the development of theory from case study analysis to include “seeing links between ideas, noticing where patterns exist, abstracting ideas from your data and offering explanations…” (p. 180); the trajectory of movement from ideas to patterns to insight underlies these statements. Data used for the typological analysis included the team transcripts, design journals, and follow-up interview transcripts.

In typological analysis the coding is based on predetermined categories, derived from “theory, common sense, and/or research objectives” (Hatch, 2002, p. 152). Using subcomponents of self-regulation theory as a starting place (from Figure 9), the first pass of data here was to annotate evidence related to the typology. Given the nature of the study, certain elements of self-regulation were obscured: self-instruction was obfuscated by having students think-aloud while designing; imagery supports for performance were not identifiable by their mental nature and the audio record; and coding for attention focusing was ignored because of the information

Table 5. *Example Transcript with Coded Design Moves and Links.*

Speaker	Transcript	#	Design Moves	Links
Sydney	I think these clips look about the same.	309	Clip arrangement in parts is similar from rebuilding	
	So that helps the math equation a little bit [just using extra].	310	Using extra silicone makes math easier (unnecessary)	
Jordyn	Yep.	311	Agreement	310
Sydney	I just want to make sure all of these are even. As even as I can without it exploding again.	312	Checking to make sure parts are even without explosion	
Jordyn	Yes. So that way it doesn't, hopefully, leak.	313	Agreement, evening out fingers will prevent leaks	312
	And he said fill it a little bit below ... Wait, there's like a fill line.	314	Seeing fill line in the mold parts	
Sydney	And you fill up to it?	315	Question to fill up to the fill line	314
	Good that these are just the testing because we can get used to the pouring process.	316	Preface fingers as a learning opportunity for pouring	314
Jordyn	Yeah. All right. So the silicone is definitely over-filling.	317	Silicone pouring is overflowing the mold	314, 316
Sydney	Yeah that's very difficult, it's very temperamental it looks like. So it's hard to get it in without ...	318	Silicone pouring process is difficult without spilling	316, 317
Jordyn	Without spilling over the edge.			
Sydney	Yes.			
Jordyn	So I guess we'll just see how that ends up drying. It probably won't be the right shape but it's worth a try anyway.	319	Decide to move on even if the spill changes the shape	317
Sydney	Yeah. It should look that should be enough. But if not we can make a little bit more.	320	Agreement to move on with enough silicone in the molds	314, 319
Jordyn	Yeah, I think it's fine. As long ... I think as long as it covers the joints.	321	Agreement, filling is enough if it covers the joints	314, 320

Note: This exchange occurred on Day 2, after assembling soft robot finger molds, while preparing to pour with silicone.

preparation process of eliminating off-topic conversation. Since the design journals I reviewed were entirely evidence of self-recording, this code was omitted from consideration within the design journals, and only applied to the transcript in situ. The utilized codes are described in brief in Table 6 and more fully in Appendix G.

After applying codes from the regulated response to failure framework, the collection of evidence was summarized by typological element, especially recording main ideas to connect in the next phases. Further analysis identified patterns, relationships, and themes by comparing evidence within each coded element (Wendell et al., 2017). These profiles were corroborated by searching for examples and non-examples in the data. Hatch (2002, p. 155) noted these connections may be on the basis of similarity, difference, frequency, sequence, correspondence, or causation. Finally, the patterns were described in succinct examples.

For an instrumental case study such as this, aggregation of the data and focus on relationships and issues from the research questions are appropriate (Stake, 1995). There is also congruence between pragmatism and typological analysis, as evidenced by the preconfiguration of categories and acceptability of "anticipated patterns, relationships, and themes [while] watching for others that may be unexpected" (Hatch, 2002, p. 156). In this way the findings match elements of self-regulation theory and the framework integrating this research.

3.5.4 Research Alignment

The research questions and theoretical framework of self-regulation represent a conceptual starting point for this research. In order to understand beginning designer experiences of self-regulation, I have chosen information sources which offer a lens into student thinking, and two analytical approaches. The analytical approaches just described complement the research questions, information collected, and one another. Figure 13 portrays the connections among these research design elements.

Observations and audio recordings were transcribed and first, scanned for design attempts and ensuing instances of success or failure. The framing of success or failure contextualizes the subsequent analysis. Next, the design process of two teams with different trajectories of success and failure were represented through linkography. This strategy provided an overview of the design process and revealed patterns of self-regulation—backward and forward thinking (Question 1). Design artifacts denote milestones in the process and occurrences of failure or

Table 6. *Typological Coding Definitions Based on Self-Regulation Subcomponents.*

Subcomponent	Definition	Example Statement
	Forethought	
Goal setting	Deciding specific desired outcomes of performance	"Yeah, we're making the mold and then we have to pump air into it." (Jordyn)
Strategic planning	Selecting strategies to accomplish the task	"I'm writing a chart out for select an approach." (Brynn)
Self-efficacy	Statements about personal beliefs of ability	"Obviously I'm not that successful at it." (Sydney)
Outcome expectations	Belief statements about the end results of performance	"I think this design will work." (Katelyn)
Intrinsic interest/value	Motivation or value for the task, whether or not there are rewards	"I'm excited to mix up this silicone." (Fiona)
Goal orientations	Motive for performance, from mastery of the concept to performance for others	"Good idea, because that could also just show us the spacing in general." (Sydney)
	Performance	
Task strategies	The use of specific strategies to aid in performance	"Let's look at the instruction book thing." (Katelyn)
Self-recording	Capturing performance progress (applied when using design journals in practice, not to the journals themselves)	"I'm finishing up the drawings." (Wes)
Self-experimentation	Varying aspects of performance or self-testing for performance improvement	"It's kind of worth a try, I guess." (Jordyn)
	Self-reflection	
Self-evaluation	Comparing performance against established standards or goals; denoting an event as a success or failure	"It's more than enough." (Evan)
Causal attribution	Developing an explanation for performance outcomes	"It's not getting pressure throughout because there's an air bubble." (Katelyn)
Self-satisfaction/ affect	Affective states as a result of performance evaluations	"Oh, no… All of my work." (Fiona)
Adaptive-defensive	Whether the learner is open to change or defensive about approaches and learning	"Well, next time we can put more in." (Taylor)

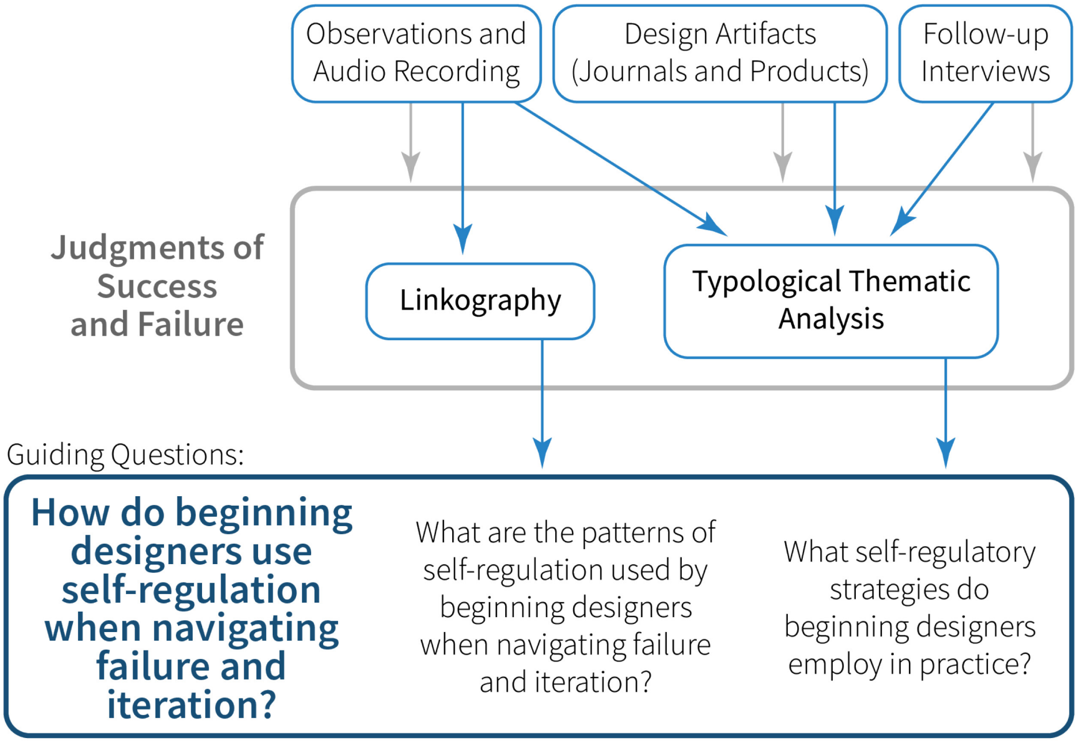


Figure 13. Information source, data analysis, and research question alignment. Information sources inform the identification of successes and failures in the participants' design experiences. Linkography and typological analysis are contextualized therein. Each works towards a guiding question and fostering understanding of beginning designers' self-regulation for failure and iteration.

success, adding new texture to the representative patterns of thinking. Next, the information sources collectively informed typological thematic analysis. The transcript, design artifacts, and follow-up interviews of all teams were coded based on the self-regulatory strategies employed. Further description and context of these codes shows the practices and supports for self-regulation of beginning designers (Question 2). Finally, these results were integrated to describe the soft robot design experience as a case of beginning designers' self-regulation.

3.6 Research Quality: Validity and Reliability

I acknowledge the need for care in retelling the design experiences and strategies of beginning designers. For clarity, I maintain the familiar language of validity and reliability as research standards (though there are certainly differing perspectives, especially among qualitative researchers). Validity is the accuracy of my work, including the description of contexts and results and interpretations (i.e., "How congruent are one's findings with reality?"; Merriam, 1995, p. 53). Reliability is the dependability of these findings, especially as related to methodological decisions and consequences (ie., "To what extent would these results be found again?"; Merriam, 1995, p. 56). Paradigmatically and methodologically I am concerned with my accuracy in representing and interpreting these experiences; to satisfy my pragmatic interest in understanding regulatory strategies and experiences of failure my account needs to be authentic to the students who encountered it; to inform design education it needs to appropriately emulate the nature of their experience with characteristics that are transferrable to the situations of others. Furthermore, related to my pragmatic focus on consequences (Cherryholmes, 1992), I am concerned to elucidate the contexts where these findings take place as a foundation for the results. Therefore, toward quality research with validity and reliability, I have applied several recommendations from Creswell and Poth (2017) who recommend at least two be incorporated: triangulation of data sources, member checking, using a codebook, and using thick description.

Triangulation is addressed by many researchers (e.g., Creswell & Poth, 2017; Merriam, 1995; Stake, 1995; Gary Thomas, 2011; Tracy, 2010; Yin, 2014). It involves using multiple perspectives to confirm findings, whether perspectives of multiple data sources, analytical methods, or researchers. Triangulation is congruent with the case research here, in that multiple information sources built a rounded description of the case. Further, the analytical approach to use macro and micro perspectives (linkography and typological analysis, respectively), in addition to searching for disconfirming evidence showed appropriate effort to understand and convey the situation truthfully from multiple points of view.

Member checking was conducted to verify my account of the design process and students' design success of failures (described in Section 3.4.3 Follow-up Interviews). In contrast to some authors who review drafts with the participants (e.g., Stake, 1995), I returned with a summary of the experience and tentative findings related to success and failure to ask for corroboration and further information (Creswell & Poth, 2017). These follow-up interviews added additional data and understanding about the design experience of students, "going beyond the goal of ensuring that the 'researcher got it right'" (Tracy, 2010, p. 844). This experience also exposed my bias in interpretations of the experience, as my reflections on success and failure differed from the participants. In reporting hereafter, students' interpretations of success and failure were used.

For consistency in analysis, I created a codebook to record definitions and descriptions of each element to be coded. Two types of codes were guided by use of the codebook: identification of design moves and links for linkography, and identification of self-regulation subcomponents during typological analysis. Past examples of linkographic methods were leveraged to define design moves and links (e.g., Cai et al., 2010; Goldschmidt, 2014; Hatcher et al., 2018). The incipient definitions of self-regulated elements were also based on literature (Peters-Burton, 2018; Zimmerman, 2000). To ground the coded concepts in the case context, the codebook was created after reviewing all of the materials, but before applying the codes; it was also expanded with examples throughout the coding process.

Finally, aligned with the case study emphasis on describing contexts holistically, I use thick description to allow readers to "transfer information to other settings and to determine whether the findings can be transferred" (Creswell & Poth, 2017, p. 263). Tracy (2010, p. 843) suggested the importance of "showing" rather than "telling" in qualitative research reporting; therefore, thick description requires decisions about the focus of results, yet allows the reader to come to their own conclusions. Thick description also entails "understanding and absorbing the context…[and] ascribing present and future intentionality to the behavior" (Ponterotto, 2006, p. 539). It is not only descriptive, it is analytical.

My complementary analysis approaches support thick description—the macro perspective offered by linkography showed a holistic, more descriptive picture, whereas the thematic analysis and evidence provided an opportunity to focus on details of the experience. Information from multiple sources is also reported to substantiate findings. I have attempted to thoroughly describe the research context from which these findings emerge—the historical development of the soft robot lesson, its current state, and my procedures for observing the experience. In the next chapters, I report results with thick description to present the rigor of research through "thoroughness" (Tracy, 2010, p. 841) and rely on the data to answer the research questions.

These strategies for validity and reliability are attempts at research quality and trustworthiness, and are critical for addressing a key limitation of this research: it was conducted by a single researcher. Having been conducted by a single researcher, reliability of the coding is not guaranteed (Goldschmidt, 2014, p. 32). Further, design dialog and verbalizations are ambiguous. Perry and Krippendorff (2013) reported on the difficulty of identifying the boundaries of design moves for students new to protocol analysis or who lacked investment in the process. These concerns also apply to qualitative coding, as conducted in the typological analysis. I took several steps to address these challenges, each described in the next paragraphs: 1) I used prefigured codes from literature, described previously in Contextual Application of Linkography, and Figure 9 and Table 6, with the completed codebook provided in Appendix G; 2) I maintained consistency in the coding schemes across multiple transcripts by adding emerging examples and clarification to the codebook; and 3) I relied on my familiarity with the design situation.

First, the prefigured nature of the codes in typological analysis somewhat mitigate the risk of chance findings by constraining the breadth of analysis to be informed by theory (as opposed to what might emerge from an inductive approach). Definitions extracted from literature provided good footing for the start of research analysis. Second, the coding schemes were applied to the process of multiple design teams iteratively, with revisions and inconsistencies being resolved along the way. In the case of linkography, two team design processes were analyzed for design moves and links in a similar manner. In the case of typological analysis, evidence from all teams was integrated to examine specifics of self-regulation strategies. Though completed by a single researcher, this approach sought to "ensure continuity of coding standards" (Snider, Cash, Dekoninck, & Culley, 2012, p. 151).

Finally, as mentioned, observations in the classroom, my time spent previously making soft robots, and investment to design previous versions of the lessons provided familiarity with the experiences of this design challenge. Time spent for in-class observations and transcription of the data are types of prolonged contact and were useful for building my own understanding of the students' experiences.

Hatcher et al. (2018), suggested there is not a "correct" linkograph, "only reflections of each researcher's understanding of the creative process" (p. 149). Because of this subjectivity, they argued integrating results from multiple researchers was "unlikely to be any more accurate or representative than the linkography on [sic] one single researcher" (p. 149). Notwithstanding the benefits that might be seen through collaborative development of the coded results for linkography and typological analysis, this philosophy mirrors my paradigmatic choices in this research—the context and outcomes (interpretations) are unique to the research, yet intended to be transferrable based on connections with the reader. My focus on consistency and transparency in the process through the aforementioned methods, coupled with my unique expertise in the design of soft robotics at the secondary level, maintains the quality and trustworthiness of the results. By accepting these limitations, applying research methods for their intended use, and interpreting the findings with steadiness, I "arrive at reliable findings and solid conclusions" (Goldschmidt, 2014, p. 34).

3.7 Summary

In planning and conducting the methods described in this chapter, I was guided by the research objective to investigate and describe self-regulatory practices of beginning designers, case study approaches, and a pragmatic philosophy. The soft robot lesson was delivered in two classrooms where four design dyads were monitored for the duration of the experience. Data collection and analysis were each undertaken with multiple perspectives in mind: a variety of information sources were used and two analytical methods (linkography and typological thematic analysis) were chosen to depict macro and micro elements of the design experience. Hereafter, I describe the case study findings, embedding my own reflection on the process and contextual interpretations or thick description.

CHAPTER 4. RESULTS

From observations for multiple days per team, and later immersion during analysis, this case study research offers a description of high school student self-regulation while designing. An affordance of the case study methodology is the intersection of multiple perspectives to obtain a nuanced view and depth of description of the case context. With this research methodology, I triangulated multiple perspectives by analyzing the account of multiple design teams, using a variety of information sources, and conducting complementary analytical approaches of linkography and typological analysis. Interpretation of the primary information sources (observations and audio recordings) was augmented by artifacts obtained from the classroom and design journals, as well as follow-up interviews with design teams. The results are reported using students' language—oral or written—to give thick description and contextual detail. In these results I illustrate the complexity of beginning designers' self-regulatory responses; the design experiences were interconnected to varying degrees.

An account of each team is described, briefly reviewing their sequences of design success and failure. Each teams' account offers a unique chronology for design problem-framing and -solving, such that the planning, testing, and reflective actions of each team offer insight into students' self-regulatory approaches. The students and classroom context and meaning-making of each team is described in their own language to contextualize further analysis.

Then, the design processes of two teams with contrasting journeys are more closely examined, including representation of design process connections through linkography. An overall characterization of the design process is given, based on linkographic analysis—this characterization includes the measurements drawn from analysis such as the number of moves, links, and the link index; the identification of critical moves; and features of the linkograph. Self-regulatory patterns are illustrated through elaboration of these features and critical moves.

Finally, results from typological analysis of the dialog and documentation spanning design teams are presented to elaborate on self-regulatory strategy use among the designers. Using the predetermined codes of self-regulatory elements (Table 6 and Appendix G) and identification of failures and successes, portions of the data were annotated. This evidence was compiled by code to extract patterns and commonalities in self-regulatory approaches. Generalizations and examples are provided as examples of self-regulation in practice.

4.1 Design Chronologies

The following chronologies summarize events from the soft robot design experience of each participating design team. These experiences are highlighted by the iterative attempts to fabricate a soft robot and the self-reaction that transpired. Based on my scan of design artifacts and the transcribed design process, attempts toward the soft robot gripper solution were identified (discussed in the Marking Success and Failure section). Each attempted soft robot finger or gripper or abandoned design, was documented along with the results. These are depicted in the snapshot presented for each team. The design process of each team is represented by day, with finger and gripper attempts abbreviated F or G, respectively, and numbered sequentially. Time spent fabricating the robot is indicated by an arrow, leading to the outcomes. The outcomes of each idea are marked as success (✔), partial success (⚠), or failure (✖). Instances of momentary success are marked by a transition from success to failure. The results of successive repair attempts are indicated in turn. I describe connections among these milestones, such as how a successful finger design was the groundwork for a gripper or the identification of failure mode led to purposeful behavior in the next attempts. Moreover, the satisfaction of each team, and their adaptive or defensive stance toward design failure, is described to illustrate diversity in students ensuing behavior.

4.1.1 Sydney and Jordyn

4.1.1.1 First Successes in Finger Fabrication

Sydney and Jordyn were assigned to work together by Mr. Gray for the soft robot design experience. Both girls were adept students and friendly, even though this was the first project they had worked on together for class. However, their initial design work was conducted individually, based on a procedure from Mr. Gray to require individual ideas be developed before working collaboratively to select an approach. The first day of class, then, was conceptual design. Because the girls did not have a context for understanding the performance of soft robots, they struggled to evaluate their ideas. However, by researching and handling the materials, they arrived at different designs for soft robot fingers. They approached it as an experiment, understanding that if it didn't work they could "fix it, change it, rearrange it" (Sydney). Furthermore, they varied their designs strategically so that they could build an understanding of how manipulation would affect performance. Their first fingers successfully inflated (Figure 14,

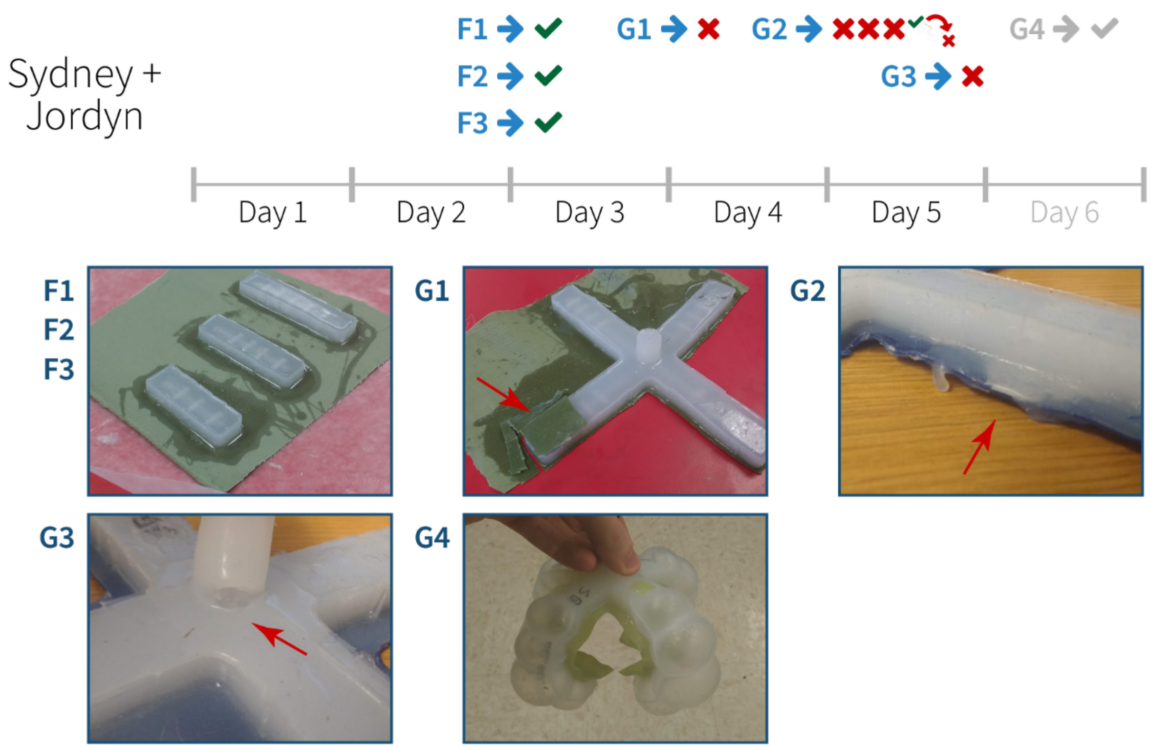


Figure 14. Snapshot of design successes and failures for Sydney and Jordyn. Finger and gripper attempts are abbreviated F and G, respectively. Iterations of each artifact type are numbered sequentially. Time for fabrication is indicated by the span of the arrow. Outcomes are marked as success (✔) or failure (✖). Instances of momentary success are marked by a transition from success to failure. Repair attempts are indicated in turn. In order to build a successful solution, the team persisted after I stopped observing; this day is included in the timeline.

F1, F2, and F3) and were clinically analyzed. From comparison of each design they chose to use a middle finger length, expressing the tradeoffs of a shorter or longer finger:

Sydney:	I think the middle design would probably be the most successful.
Jordyn:	Yeah.
Sydney:	And I think we should just go with that.
Jordyn:	Agreed. The smaller one is easier to inflate. But I don’t think that it would have as much of a grip on the objects. Whereas the longer one is pretty difficult to inflate because there’s more area for the air.
Sydney:	And I feel like it curves almost too much. So less round things are probably harder to pick up with this longer one.

4.1.1.2 <u>Navigating Failures in Gripper Fabrication</u>

The transition to fabricating a gripper proved more challenging than expected. The two noticed that the mold was curving up on their first gripper; therefore it was not filled up enough for the inner air chambers to be sealed, and they attempted to reposition the rubber band to correct it. This fix was futile because when loading the gripper into the oven, a rubber band broke and the mold fell apart. They reassembled the mold, salvaging as much silicone as possible, which remained futile because, when loading the gripper into the oven once more, rubber bands broke and the mold fell apart again. Eventually they deliberately reverted to the rubber bands used for their fingers, their first gripper was left out to cure overnight, and the two were left to say, "It is definitely frustrating to be put back…. At least we know what happened, we can fix it. Then we should be able to get a head start on tomorrow" (Sydney). The next day, when taking their silicone layer out of the mold, it was too thin on top and broke. The teacher suggested a preemptive repair by trying to attach fabric to cover the hole, but the team began "mentally preparing to possibly make another hand because of the issue" (Sydney) and even assembled another mold "just in case" (Jordyn). Even before testing, the team was doubtful the first gripper would successfully inflate, let alone be able to hold an object according to the design challenge. The first gripper did not inflate at all and was assumed to be leaking from the patch so it was quickly thrown away (Figure 14, G1); only a comment or two transpired before the team filled the second gripper mold to try again.

The quick reaction to the first gripper failing was probably precipitated by several aspects surrounding its construction. The team had faced challenges in constructing it and seen obvious weaknesses in along the way. Without the suggestion from the teacher, I question whether they would have proceeded to attach the fabric layer and try to repair the hole. Furthermore, by the time of testing, the team had already taken significant steps toward another attempt—the second gripper used the same design because the failure was attributed to materials, not the design decisions.

In preparing the second gripper (Figure 14, G2) the team was attentive to the rubber band and mold problems that had affected their first gripper: "I'm worried that maybe once we attach all of the rubber bands it'll start to bend. So hopefully that won't happen and we won't have that issue again" (Jordyn). Instead, a different issue was seen immediately before testing—there was a gap in the seal between the silicone elastomer and fabric layers. Even when held, the gripper leaked and the team decided to "just reseal the whole thing" (Sydney). In a back-and-forth of testing and repair work, what felt like a trial and error process to the team, they were able to have fleeting success. The second gripper inflated, to the elation of the team.

Sydney: It was working.
Jordyn: Oh, I love this project.
Sydney: Now that it might actually work I'm very excited.
Jordyn: I agree.
Sydney: We're almost there. We're reaching the summit.

When it was finally working though, the gap in the seal burst to their devastation. Jordyn's breath caught before she said, "My life is ruined" and then settled her reaction, "It's ok. Maybe we can reseal it. Again." The final repair attempt on the gripper happened in parallel with the start of the third gripper, and still did not work.

In the midst of conducting repairs, the team made another replacement mold for gripper three, to mitigate failure in the design process. The team was "in a desperate attempt to get [it] to work" (Jordyn). The team acted on their observations from the first attempts—they were careful to have the rubber bands sit evenly, reinforced the seal in the same was as their fingers, and cured the gripper on wax paper to support the seal. Sydney said, "I definitely feel with all our mistakes we've definitely helped learn what to do and what not to do. So I think hopefully this will work." Even with the lessons from failure cascading through the regulatory and design process, the team made a new, crucial error when adhering the silicone elastomer and fabric layers, which was vocalized, "I know it says lightly press [the layers together] but that doesn't seem to be working" (Sydney). Instead, the team roughly pressed the layers together, which clogged the air chambers, prevented airflow, and caused the coupler to rupture when they tried to inflate it later (Figure 14, G3). And they were unable to manually open the passageways. At the conclusion of my observations the girls tried to manage their reactions through statements such as, "Well, a good effort" (Jordyn) and "We tried really hard" (Sydney), though they told a neighbor that the process went badly. For their persistence, Sydney and Jordyn continued on the project the following day and were able to make a successful gripper. They told me it had an air bubble that needed to be sealed but was ultimately successful (Figure 14, G4).

4.1.1.3 Summary and Implications

An overall pattern teased out of the design process of Sydney and Jordyn was their persistence and adaptivity in spite of failure. Their initial successes were analyzed to determine the best route forward, and for most of their grippers, they attempted repairs. Though not necessarily evident from the repetitions of failure, information from earlier attempts was used to shape later attempts. The first gripper was unsuccessful due to the mold bending under tension;

in subsequent attempts the team members were careful to monitor bending and change parts or rubber bands if necessary. The second gripper had an improper seal to the fabric layer; in an overreaction, the team roughly pressed the seal of the third gripper. And by the fourth gripper they reported being “meticulous” (Sydney) and “following every direction explicitly” (Jordyn). While success in the project was important, judging by their reactions and satisfaction, each team member recognized learning was an important component of success, a “physical, but also educational success side of it” (Jordyn).

4.1.2 Evan and Fiona

4.1.2.1 Starting Slowly

Evan and Fiona were also in Mr. Gray’s class but sat close enough that they began the design process informally, despite the tradition of starting on individual work. Both students were gregarious, often interrupting their work for conversation with others. Their beginning conversation oriented the project to focus on making a robotic hand for picking up objects without damage. Evan quickly restated the process to design and test fingers, before building “four of those fingers” for the gripper. They recognized a few opportunities for flexibility in the design process early on: number of clips, even spacing of clips, making a bigger or smaller air pocket at the end, or changing length. However, team decision-making was out of harmony. When Evan stated a number of clips, Fiona responded, “Yeah I think five sounds like a good number. I’m still not done with step one though.” Evan had quickly moved through the design process (though superficially), while Fiona was being more thorough. At Step 3, research, Evan’s tempo was reigned by external expectations about completing all of the design process steps—for the teacher and the grade. But his synthesis of research only drew from the video resources that had been provided. Fiona uncovered some advanced materials from an online search related to soft robotics, but said “I don’t want to do this” as the first day of class ended. The research of both team members stopped short of informing their fabrication.

The second day of design for Evan and Fiona remained conceptual rather than moving on to fabrication. While Fiona worked through her design process documentation, Evan stated, “I already know what I want to do.” And his input while she was completing her work led to meandering conversation—for example, she began to evaluate her second idea before debating the pattern for what finger designs would be tested and possible design variables, finally making it back around to complete the evaluation. When starting evaluation of the third idea, the comments competing the evaluation circumscribed off-topic conversation about school testing, the possibility of racing the robots, and that the robots did not actually locomote. The challenge of predicating outcomes in the unfamiliar setting wasn't acknowledged at first by these two designers. Only later did Fiona ask, "How can I make pluses and minuses [to evaluate ideas] when I've never done this before so I don't really know?" Evan and Fiona negotiated design ideas, trying to balance between what they thought was a "more practical, basic, and safe design" (Fiona) and one that was "more of an out-there idea…. [with] a larger chance of failure" (Fiona). By the time the two were ready to begin working together to make each finger for testing, they reasoned there was not enough time and they would need to wait until the third day.

On the third day, Mr. Gray began by describing the fabrication process and handing out instruction sheets for all students, because most had not been ready the day before. The class collectively moved into the lab room to work on fabrication; even if teams were not finished with their individual steps, they were told to complete them in the back. In his instruction, Mr. Gray reminded everyone that the point was to iterate—from the finger designs to the first hand, and from the first hand to a second, because "even if the first one works well, you can always have it work better, right?" Evan and Fiona clarified that the point of the soft robot fingers was for testing.

Evan: The purpose of this is just like so we don't screw up the first time. Like we can mess these up and then it doesn't matter.
Fiona: Oh wait, so the ones we're making now are the ones we're testing to see which ones are the strongest?
Evan: Yeah. So it doesn't really matter.

Even while Fiona was finishing her documentation and evaluation of brainstormed ideas, the team wondered what ideas to make with the mold parts. Fabrication started with a "base" design (Evan), "a good one" (Fiona) they thought would work. Changes to that design were considered as alternatives but Evan said, "those ones don't matter." Soon, four fingers were built and Fiona "felt better because we actually have stuff done" but the fingers were not finished until the next day.

4.1.2.2 Short-Lived Successes

When the team made it to the back room the next day, and demolded their fingers, one of the first observations was a hole in the top of finger one (Figure 15, F1). The teacher was pulled

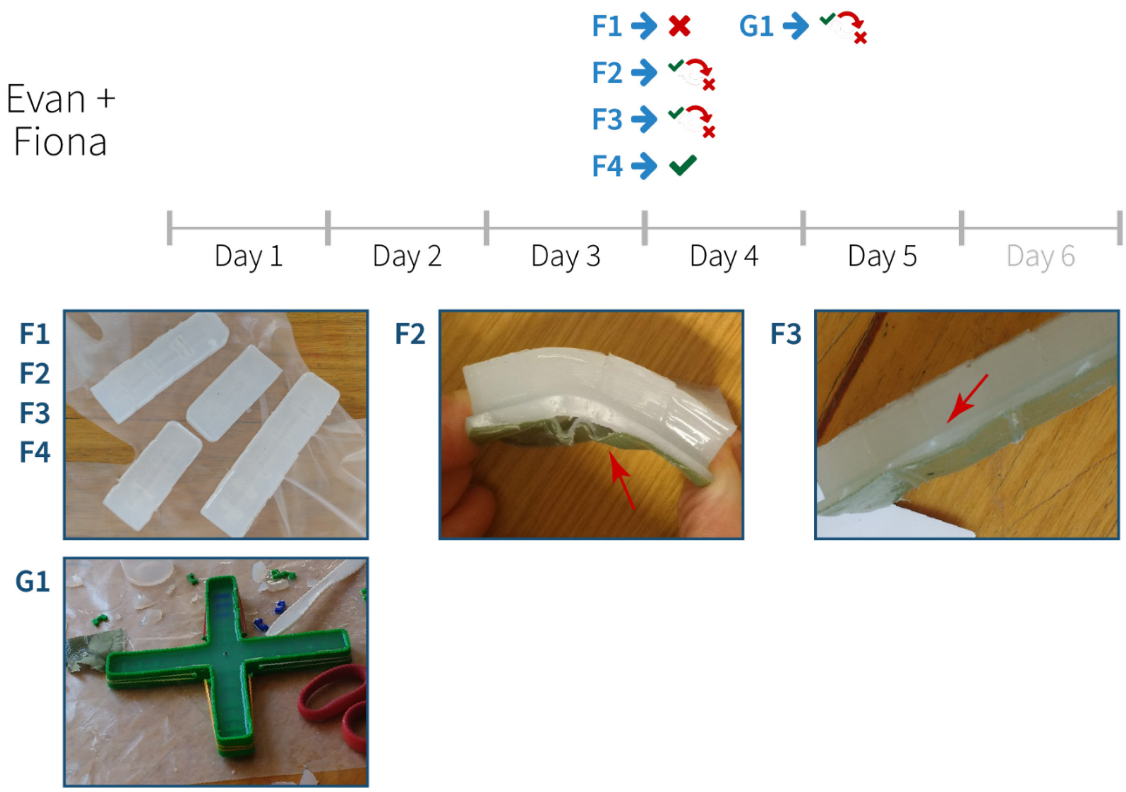


Figure 15. Snapshot of design successes and failures for Evan and Fiona. Finger and gripper attempts are abbreviated F and G, respectively. Iterations of each artifact type are numbered sequentially. Time for fabrication is indicated by the span of the arrow. Outcomes are marked as success (✔) or failure (✖). Instances of momentary success are marked by a transition from success to failure.

over to investigate and uncover what had caused the failure—a clip had floated up in the mold while it was curing. The team members had immediate concern about whether it was the "good one" and whether there would be points taken off for only having three fingers. Next, the team worked on attaching fabric to the remaining soft robot fingers; this required an impromptu review to remember the process, "Yeah we need fabric. Uh, we probably should figure out how to do the fabric then" (Evan). The team was able to navigate the process, relying on handouts given previously, and making a few trips to collect supplies. A quick bypass was taken on the way to the toaster ovens so that the adhesion between the fabric and silicone elastomer layers could be repaired. About 15 minutes later testing commenced. The second finger worked temporarily before popping at the seal (Figure 15, F2); this result was promising at first, but quickly framed as a lesson learned. Fiona's comments juxtaposing the event were, "This is so cool…. No. This is our test. Now we know this one isn't good. There you go. You're welcome."

The third finger was the favored design and eventually burst, but not before being judged “the best one” (Fiona; Figure 15, F3). It was analyzed for the potential reasons for failure: “needing “to cure longer” (Fiona) or “need[ing] better sealing” (Evan). The last finger was smaller and successfully inflated (Figure 15, F4), but because the failures were not seen as design-related, the team proceeded with the third design for their gripper. I helped the team along at the end of the class by reminding them they could cure the silicone overnight in the molds; the team members were waiting, when I asked “If you pour the silicone in, do you remember how it cures?” This revelation was followed by another observation that allowed the gripper to be accurately finished that day: Fiona saw that clips were floating up in the silicone again, and the team was able to replace them. Replacements were made by trial and error in a messy process, dripping silicone on the table from the bad clips. And the team felt “lucky [they] didn’t put it in” (Evan) the oven to cure.

The last morning, there was confusion about how to attach the final parts of the soft robot together. After initial disagreement, Evan and Fiona realized they had “messed up the order” (Evan) for some of the steps and would need to wait for more parts to cure. The mistake derailed Fiona’s understanding of the process, though Evan had worked out what needed to happen.

Fiona: Ok. We are literally not following the directions anymore because we screwed up and we are just going to look and guess that it’s cured.

Evan: We’re not guessing. I know what I’m doing. You know what? When it works, I’m going to sit here and tell you I told you so.

There was not a shared understanding and Fiona felt that “if it fails, it’s our fault…because we didn’t read the directions right.” During finishing stages of fabrication Fiona read the instruction packet “word for word” and said, “I should have looked over this whole packet.” One standout from the packet was a section on repairs that was mentioned, “if the gripper gets a hole we can make another batch of silicone and then try to repair it” (Fiona).

However, when it came down to it, the team circumvented any repairs by how they framed failure. When testing the gripper “it didn’t fully inflate like it should” (Fiona)—there was dramatically uneven inflation and the team had to manually open up airways—but it was able to pick up a marker for a few seconds as the team experimented (Figure 15, G1). Just as the team was showing the teacher, to demonstrate picking up the required objects, it popped. Conversation afterwards shifted from “So we can repair it though” (Evan) to “But it worked, so it’s fine, ‘we’re done” (Evan). Evan was satisfied that it was successful and the team was done. And once

Fiona was convinced that their design performance could fulfill expectations for documentation, she was satisfied that "all we have to do is fill everything out." Evan completed his documentation more hastily than Fiona, whose documentation evoked reflection about the process and hypothetical improvements.

4.1.2.3 Summary and Implications

I observed that the design and regulation of Evan and Fiona was disjointed. Evan conducted only perfunctory documentation of his work, while Fiona was more detailed. This difference led to instances, especially in conceptual design and concluding documentation where the team was working on separate phases of the process. At these times, attempted collaboration was circuitous; in contrast, hands-on fabrication stages of design served to unify the team's progress despite the just-in-time learning that was required. As a simple indicator of process management, Evan and Fiona had the least on-task conversation among the design teams observed (see Table 4). The team also fixated on the design idea for their soft robot gripper, despite evidence that may have supported other ideas. In terms of the self-regulation process, this illustrated a disconnect between performance and reflection, and a defensive stance to avoid change.

The task orientation of the team also centered on external values, such as points or class procedures. In cases deemed a success, even when short-lived, the performance orientation of the team may have aided in their framing of the event and eventual satisfaction. The manner in which Fiona was convinced to simply document their gripper results, rather than making repairs or further iterations, is suggestive of this mindset. In cases where performance was judged to be unsuccessful, I believe this performance orientation allowed the team to quickly abandon approaches. However, the performance goal orientation similarly abandoned reflection or deeper learning from the failure occurrences.

4.1.3 Brynn and Katelyn

4.1.3.1 Incremental Improvements

Context for the soft robotics lessons—scientific principles, examples of other soft robots in action, and an overview by the teacher—had set the stage, so that on the first day students were designing and fabricating their beginning ideas. Teams in Mrs. Childs class worked collaboratively from the start of the project. Brynn and Katelyn retrieved a bag of mold parts for the soft robots (Figure 3) and rearranged the parts to propose different ideas. Katelyn suggested varying the length and Brynn, the clip arrangement.

Katelyn:	The pieces don't connect. Oh wait, there's one. There, that would… We should make a long finger, and then we should make a short finger, and then a medium finger. And see which one would curve the best. You feeling me?
Brynn:	Hang on, what? … Now we need to brainstorm?
Katelyn:	Yes. So, this is just where we really pick different possibilities, right?
Brynn:	Well, yeah. That's where we can define, like, pick where we put the clips.

They recognized that to test their ideas they would be fabricating each finger, that is when "we discover what's going on" (Brynn). Proposed ideas were met with "we can try" (Brynn). Compared to the video examples they had seen, the team "didn't think that this [project] would be that easy" (Katelyn). Brynn and Katelyn asked their teacher numerous questions along the way to understand the process, notwithstanding the instruction to ask other people and use other resources first. By the end of class they had completed the silicone layer of their first finger.

Most of the class was synchronized for the first day—they had cast the elastomer layers of the first fingers. Mrs. Childs provided instruction about the next steps, attaching the fabric layer, with the advice that "I can save a lot of time, you a lot of time and me a lot of time, if you just listen to what I have to say." Students were instructed to make and test each soft robot design in order, so that they could see how the first worked and how to do the second differently. Brynn and Katelyn were comfortable to plan different tasks simultaneously, and then regroup afterwards. So Brynn mixed the silicone to adhere fabric, because it had "worked out good" (Katelyn) when she mixed the day before, and Katelyn acquired other necessary supplies. The team was perceptive while finishing the first finger—they remembered details like using wax paper as a work surface, avoiding air bubbles, having a slow mixing speed, spreading a layer of silicone evenly on the fabric, and sealing around the finger to reinforce the connection between layers.

Once the first finger was curing, they started making a second finger so they were not "sitting around doing nothing" (Katelyn). Mrs. Childs caught them and warned them that they would not be able to tell what to do differently. However, they had already started and should just finish it now. The girls were optimistic that the finger had been done correctly, but nervous when it came time to test. The first finger was unsuccessful because of a hole in the seal (Figure 16, F1). Soon after, the second finger was removed from the oven and the team saw that some clips had floated up. They decided to keep working with the finger but expected big holes where the clips had been. The team adopted the lessons learned and planned to make incremental progress.

Katelyn: [retesting the first finger] We need to try to get less air bubbles because look… that air bubble looks like it's about to pop.

Brynn: Yeah I know. We secured it better this time. It doesn't look bad; we just need to make sure it gets all the way.

Katelyn: Yeah. The problem was there was an air bubble down here.

Brynn: Yeah. I feel like our second finger is going to be better.

Katelyn: No, because it's going to have holes in the top. From the clips. So the third one, the third one will be it.

When Katelyn pumped air into the second finger, it grew and then "exploded" (Katelyn) so quickly that Brynn missed it (Figure 16, F2). Compared to the layers being improperly sealed, this cause for failure was more frustrating. Still, taking the lesson into account, Katelyn shook the third mold design upside down to be sure the clips were firmly attached.

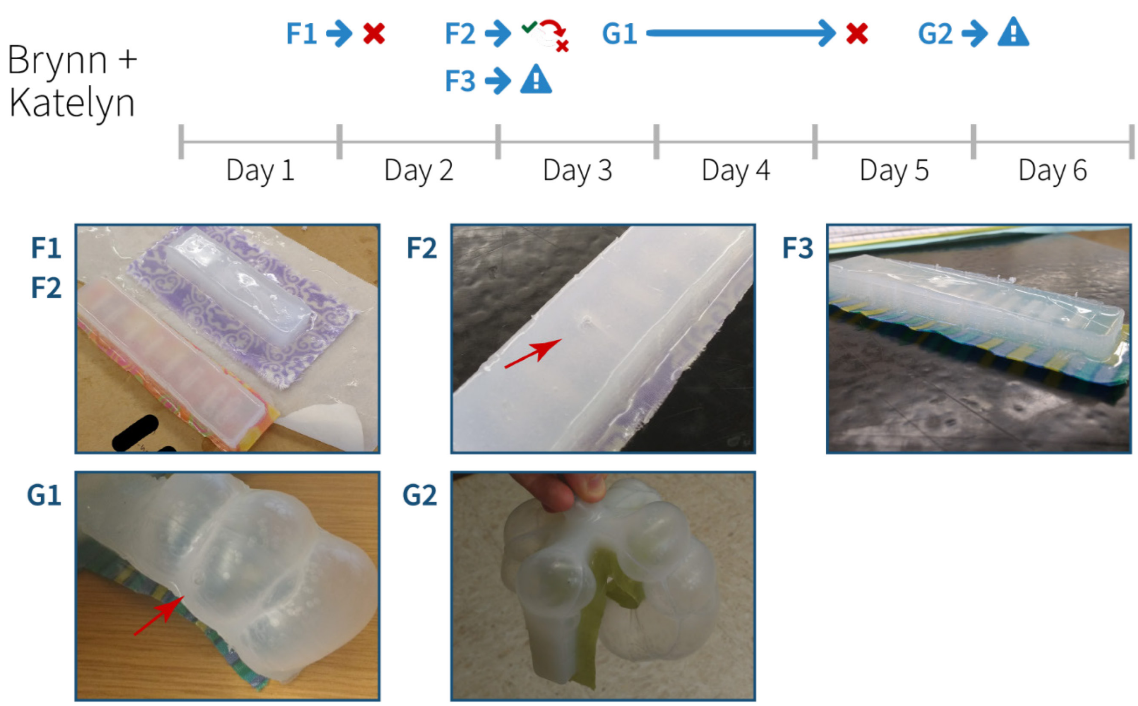


Figure 16. Snapshot of design successes and failures for Brynn and Katelyn. Finger and gripper attempts are abbreviated F and G, respectively. Iterations of each artifact type are numbered sequentially. Time for fabrication is indicated by the span of the arrow. Outcomes are marked as success (✔), partial success (⚠), or failure (✖). Instances of momentary success are marked by a transition from success to failure.

By the third finger, the team was efficient in the fabrication steps. With downtime between fabrication stages, they documented the process, even planning charts to help in decision-making and comparing ideas. When adding the fabric, the girls noticed that the third finger was “off of level” [and]” must have been tilted” (Katelyn) in the oven. The top layer was sealed and they proceeded to finish and test it. The test outcomes were confusing, and took some processing to understand. The finger only inflated at one side because the top layer was thinner (Figure 16, F3). But it was enough evidence that a decision could be made to go with the first finger design.

The process of making Brynn and Katelyn’s first gripper spanned a few days because they were not able to finish and fill the mold on Day Three and at the end of Day Four it was being cured. Several preventative actions were taken to ensure the success of the gripper. Loose clips were replaced before filling the mold, and the team reinforced a thin area on the elastomer top, based on suggestions from a neighbor. The gripper looked good at first, and appeared to inflate. Yet the inflation was uneven and stretched to make hole in the top from an air bubble (Figure 16, G1). Midway through the class, the team regrouped to identify problems and decide how to change their idea or if they would just do the same one over again; Mrs. Childs had said, “either decision is fine.” Several problems and solutions were identified—the air bubbles, which could be mitigated by stirring slowly being lucky about “where they fall” (Katelyn); having even thickness in the fingers, by making sure the mold was level; and having consistent bottom thickness by checking the silicone spread. The team then made their last iteration, the same design but a refined process.

After integrating these ideas to fabricate a new gripper, the test was partly successful (Figure 16, G2). Compared to the first gripper that “didn’t even really blow up at all” (Katelyn) there were new problems and solutions. First, the robot began to inflate in the coupler, yet was dormant through the other air chambers. The team succeeded in manually opening some of the air chambers, leading to uneven inflation. Finally, when holding the coupler tightly, the gripper was able to pick up objects “for a second, or two” (Brynn). Katelyn said the result was “successful but not quite successful” which I interpreted to mean partly successful. The team’s closing documentation noted hypothetical solutions that they could have been enacted in another iteration, but the team was done.

4.1.3.2 Summary and Implications

The progress of Brynn and Katelyn reinforced, to me, the socio-technical context in which design and self-regulation take place. Because construction of the fingers was framed as research, the team had a basis for judgment of ideas at the time of selecting an approach. Ideas were compared against actual, rather than theorized performance. Moreover, consequences that may have resulted from the team's naïve understanding of technical aspects of the project were reduced by their reliance on contextual supports. Another element of the contextualized nature of these processes was demonstrated when the team tested their second gripper: it's performance was gauged relative to the first gripper. Though "not quite successful" (Katelyn), it did operate better than previous attempts. In conclusion, the team identified hypothetical changes that could be made to lessen the risk of failures in another iteration; unfortunately, these insights were not leveraged once more in practice.

The team remained adaptive throughout the process, taking information and evidence to inform their next steps, and was satisfied with their incremental improvement. Throughout the process, the team relied on the teacher, peers, and documented resources to inform their process and technology development. Especially as the team learned the process, they asked questions immediately; however, even when comfortable with the process, they shared results with other teams and solicited advice. Interestingly, when I tested their final gripper I was able to successfully inflate it, taking some of the precautions they had discussed (like holding the coupler to keep it from inflating). When I showed the team in our follow-up interview, they were surprised, but then said, "I think if we would have just sat there and blew it up some, … and stretched it out some more then it would have eventually worked" (Katelyn). This reflection was again used to frame conceptions of success and failure, and shifted their reactions to say their own design was successful.

4.1.4 Wes and Taylor

4.1.4.1 Investigating Early Ideas

On the other side of the room in Mrs. Childs's class, Wes and Taylor worked together on their soft robot design experience. Previous repetition of the design process instilled a starting point for the team: they referred to previous notes on the process, discussed and refined the problem statement to make a gripper, and brainstormed alternatives such as finger length, clip arrangement, and clip grouping. Taylor suggested making one "really small" and then one "normal size." Wes was eager to make an idea with different clip arrangements, "one clip, two clips, three clips" in groups. Individual contributions moved to team collaboration when they needed three total ideas, based on their previous design assessment. They added a "really long one just for an experiment" (Taylor). When it came time to make the first finger (one at a time), they began with the small one that cured overnight. Perhaps not by coincidence, the construction of soft robot fingers proceeded in the order in which they were proposed while brainstorming (Figure 17, F1, F2, F3).

Class began with the advice from Mrs. Childs to listen and follow her instructions as she explained how to add the fabric, and to make one idea at a time to know how to improve. Wes and Taylor assembled a second mold before their first finger was completed, trying to remember what they had decided to do in their previous brainstorming conversation. While the team waited for the first finger to finish they had downtime, but wanted to keep building. The first finger worked "really well" (Wes) but was "not the best design ever" (Wes; Figure 17, F1). Although

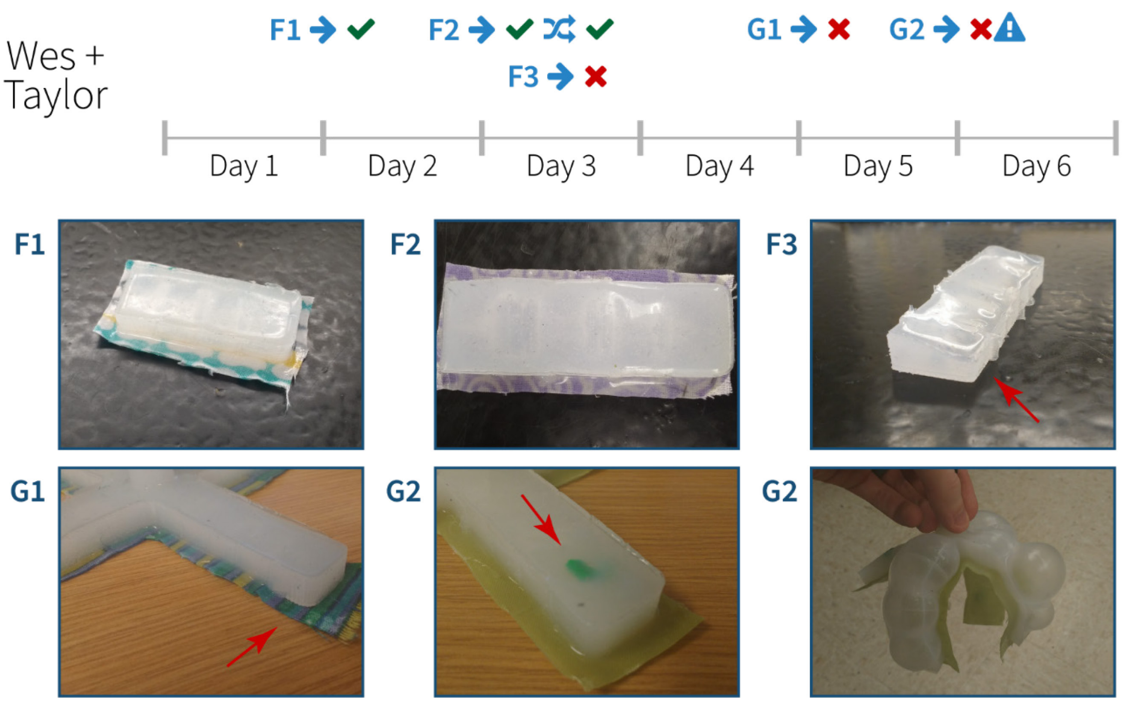


Figure 17. Snapshot of design successes and failures for Wes and Taylor. Finger and gripper attempts are abbreviated F and G, respectively. Iterations of each artifact type are numbered sequentially. Time for fabrication is indicated by the span of the arrow. Outcomes are marked as success (✔), partial success (⚠), or failure (✖). Reconfigured testing is indicated (🔀). Repair attempts are indicated in turn.

the first one was not bad, Taylor and Wes agreed that they would prefer a longer design to the short one that had been tested. Wes also suggested "bigger air pockets" because "the way it blows up it doesn't really do anything." He hoped that changing the air pockets would make it bend further. Wes continued to linger on the fabrication of the first finger, noticing its characteristics, findings ideas for improvement, and continuing his evaluation.

While he ruminated, Taylor built the second finger mold and prepared silicone. Once Wes was ready to move on, the team loaded the silicone to be cured, and he excitedly shared their design idea with those around him.

Wes:	We have our second one in the oven.
Neighbor:	That's good.
Wes:	Are you making one just like this?
Neighbor:	Except we're going to change the chambers around.
Wes:	No. You know what I think you should do? I think you should do what I'm doing on the one I have in the oven right now... is I have three chambers in the back, two in the middle, one in the front. I think you should do something like that.

Recognizing that their time would be short at the end of class, the team prepared to attach the fabric and quickly put it back in the oven before class ended. The test was successful in class the next day (Figure 17, F2); the second finger "actually work[ed] really well" (Wes) and actuated with a "nice curve" (Wes). Another test was also extracted from the artifact—Wes was interested in a clip pattern the reverse of what had been done (1, then 2, then 3). By turning it around and holding the first puncture hole closed, he was able to conduct another test of his idea. The subsequent test inflated but proved unsatisfying based on how it inflated.

The team was still interested in making the finger longer, and said, "we've got to see the other one to see which one's better" (Taylor). Ultimately, though, they abandoned the test of their long finger design because it was tipped sideways in the oven (Figure 17, F3). Wes could "feel the clips through the silicone" and said it was not a success, but Taylor reprimanded him not to judge it. When the finger was demolded there were three holes in the top and Taylor changed her evaluation, accepting that it would not work.

4.1.4.2 Revisiting Findings for Gripper Fabrication

Wes and Taylor integrated the finger test results and predictions to the design of their gripper. Revisiting the same design variables—length and clip arrangement—as well as the material constraint of how many mold parts they had, they selected an approach to have a medium length and clustered clip arrangement. The team noticed the mold parts curling up under tension of the rubber bands, and deliberated with the teacher before replacing some parts. It is possible that this challenge distracted from the details of the process because a moment later Taylor remembered that the clips had not been put in yet. There was not much silicone in the mold yet, so the clips were easily inserted and the process finished. Therefore, while demolding the silicone, Wes found a thin layer of silicone over the clips, that was not enough to be problematic. While the first gripper attempt was in the final curing stage, Wes and Taylor reviewed their design process documentation, filling in the details they hadn't written so far on constraints and criteria, evaluation of the ideas, and a detailed design drawing. A struggle with inserting the pump built anticipation for the design test. The gripper did not inflate, and the team felt and saw a gap between the elastomer and fabric layers, resulting in a permeable seal and design failure (Figure 17, G1).

The second gripper was a rapid response in an effort to have success. At this point the team recognized, "it's actually a lot harder to build than you think" (Wes). When the team saw clips had floated up into the elastomer layer, they responded by pressing forward anyways.

Wes:	So, should we even make the coupler for this?
Taylor:	Yeah, because it could work.
Wes:	There's a hole in each of the fingers.
Taylor:	Yeah, just do it anyways. I mean this is our last one. We're going to see if it works.

A nearby student pitched in that his previous attempt also had floating clips; now, he suggested sealing on top of the gripper again, while attaching the fabric. They tried "paint[ing] over the top of it" (Wes) to fill in the holes. Still, the team was unconvinced their gripper would work, telling another team as much. Even before their test they documented that it "didn't grab well, because we know it's not going to grab well." After finding and closing a hole by hand, the gripper did inflate. So the team added extra silicone to try to plug the hole. The gripper was partly successful in the end, two of the fingers inflated well, and two did not inflate very well, but it was airtight (Figure 17, G2).

4.1.4.3 Summary and Implications

Wes and Taylor began their design by each proposing an idea; in order to meet the process expectations, they generated another idea and were willing to see it through when fabricating their soft robots. They also seemed to have an adaptive, integrated process, where findings from the finger performance were used to scaffold their gripper design. I noticed a distinction between team reactions to each gripper failure. In the first case of the seal being poor, the team quickly continued. In the second gripper where the top needed to be reinforced, they made a repair attempt. It is possible that similarities between the clips floating up (an obvious problem to which a neighbor suggested a solution) and the holes in the top surface drew the team's attention to make the repair. Alternatively, perhaps the routine of the process—making attempt after attempt—led to the next attempt without analysis of what could be done. While the final attempt was only partly successful, it is possible that the first gripper could have been repaired and seen a successful result as well.

4.1.5 Selecting Focal Teams

Among the teams' experiences and reactions, I observed differences in forethought and reflection phases of the self-regulation conducted by teams. Submitting that information from forethought and analysis phases of design carries to performance and interpretation phases, differences in motivational beliefs and goal beliefs introduce varying patterns of self-regulation. Likewise, because self-regulation and design are cyclical—information moves from iteration to iteration—students' reaction to failure or success determine future trajectories. The elements of self-reaction—self-satisfaction and adaptive stance—have theoretical bearing on whether, and how, a team will proceed to iterate.

Taking determination as evidence of goal orientation, Evan and Fiona acted defensively, with a performance goal orientation. They did not make any repair attempts and, when they could communicate that their gripper was successful (even if not for long), they concluded their work. In contrast, the other teams showed an adaptive stance by making repairs or new attempts to produce a gripper that would successfully inflate and curve. Impacted by team mindset, the adaptive or defensive stance taken when reflecting on performance also differed by team. I claim that Evan and Fiona adopted a defensive stance that fortified their perceptions of success, even if fleeting. Whereas, the other teams portrayed an adaptive stance, inferring changes to make based on the performance of their previous designs.

Next, each team experienced multiple successes and failures in the duration of this experience. The teams also had ample opportunities for reflection and iteration, as evidenced by the number of phases of fabrication and testing. The sequences of success and failure test outcomes served to further differentiate team experiences. Evan and Fiona saw spurts of success throughout the experience. Their first idea was abandoned and not tested; the choice to move on was deliberate rather than forced. Disagreement about perceived success between the two students was resolved by negotiation, and Evan and Fiona concluded their design process. The teams of Sydney and Jordyn and Wes and Taylor both began with initial success before experiencing failure and success again. Brynn and Katelyn progressed from unsuccessful ideas (with identifiable problems) to mostly successful ideas. Conceived as trajectories over time, these pathways might look like Figure 18. Evan and Fiona's and Sydney and Jordyn's thinking and experiences were, therefore, contrasted in both elements of self-regulation and sequences of success and failure. The experiences of these two teams were carried forward for closer analysis using linkography, before returning to the broader self-regulation strategies applied across teams.

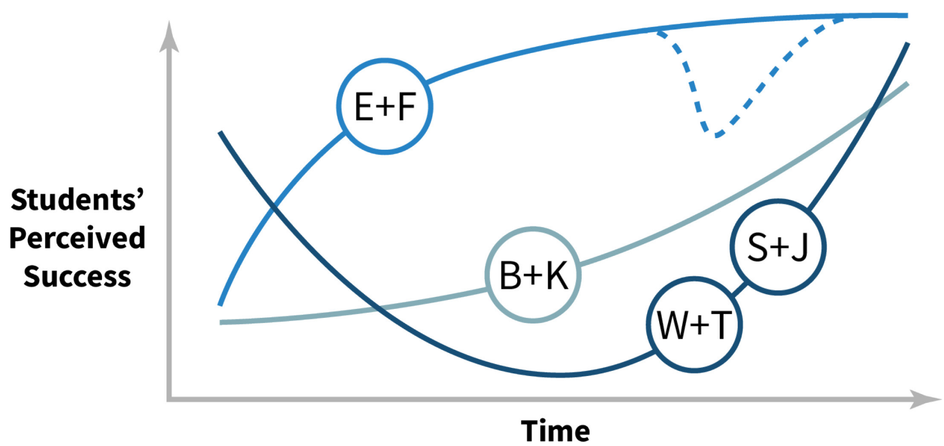


Figure 18. Theoretical trajectories of teams' perceived success and failure over time. Each circle identifies team initials aligning with the identified trajectory.

4.2 Linkography Results

The selection of teams for linkographic analysis was based on perceived distinctions in elements of the regulated responses to failure framework that guides this research (Figure 9), as well as sequences of success or failure experienced by the teams (Figure 18). Two teams, Sydney and Jordyn's team and Evan and Fiona's team, were selected for closer analysis before returning to a thematic analysis across teams. As nested units, analysis of these two teams speaks to the role of students' self-regulation pertinent to the broader case study. My summation and interpretation of these events has been described in each of the preceding design chronologies. Having selected the two teams, linkography evidence was formulated by following the procedures in Chapter 3.

From my immersion in these accounts, I portray the design process practically, turning to information that conveys a range of self-regulatory responses. Descriptive data and overall representations of the design process are given. These include metrics of the linkograph for each team—number of moves, links, critical moves, and so on—along with a qualitative description of features in the representation—chunks and webs. The linkographs portray, at a glance, the nature of the design process and are used to uncover the structure of self-regulation and design thinking (Blom, Haupt, & Bogaers, 2018; Goldschmidt, 2014). Afterward, emergent patterns are attended to, and supported through recitation of the design account. By jointly presenting these patterns and the design account, I give further thick description of the context of design and self-regulation.

The collection of cognitive evidence, through the identified design moves and links, was a mass of information. Each team made numerous moves throughout the design process, with an increasing number of possible links among them. Each *n*th move added the possibility for $n - 1$ additional links, making it labor-intensive (Goldschmidt & Tatsa, 2005). To be transparent in the process, I acknowledge the challenge of analyzing such a corpus; however, I attempted to analyze this information with consistency by using a codebook and thoroughly reviewing previously identified design moves to search for links. Furthermore, the report is not intended to be a commendation or reproach for either design team, its purpose is to show a range of patterns of self-regulation in iterative design, failure, and success.

4.2.1 Overviewing the Design Process

Sydney and Jordyn had 1,433 design moves over the five days I observed their process, with 1,026,028 possible links among them (Table 7). I identified 2,889 links, a link index (density) of 2.02 compared to their design moves. Evan and Fiona had 1,269 moves, 804,546 possible links, 2,412 actual links identified, and an index of 1.90. Link index is fairly stable in past research, around 2.0, though it hints at the flow and synthesis of design (Goldschmidt, 2014). The link index of both teams was in the expected range relative to past conducted studies, with Sydney and Jordyn having a more interwoven process.

Table 7. *Linkographic Metrics for Focal Design Teams.*

Design Team	Sydney + Jordyn	Evan + Fiona
	Descriptive Metrics	
Total Moves	1,433	1,269
Total Links	2,889	2,412
Link Index	2.02	1.90
Possible Links Considered	1,026,028	804, 546
Link Span	94.23	69.59
	Link Directionality	
Backlink Only Moves	396 (27.6%)	268 (21.1%)
Forelink Only Moves	35 (2.4%)	17 (1.3%)
Bidirectional Moves	979 (68.3%)	975 (76.8%)
Orphan moves	23 (1.7%)	9 (0.7%)

An element of divergence from expectations was the average link span calculated for the teams, 94.23 and 69.59, respectively. Based on the memory heuristic of 7 ± 2 for short-term information handling capacity, Goldschmidt (2014) suggested that most links would be formed to recent moves. However, she noted the link span is impacted by contextual factors, such as the length of the design process, working in teams, or reference to past artifacts of design (Goldschmidt, 2014), which is certainly the case here. In this case, spans were much further, on average. The link span metric alludes to the instructional nature of the design experience, its embedded pattern of teamwork and of iteration, and the length of the process analyzed. While cognitive acts early in the design process (viz., design analysis and self-regulatory forethought) would certainly be referenced later, I believe the instructional setting of this activity amplified these processes. Teams began the design process with preliminary instruction to compensate their naïveté. The daily beginning of class included a reiteration of fabrication instructions, calling back to the former instruction. Furthermore, teams began the process individually, as a tradition in Mr. Gray's classroom, and necessarily synthesized their individual work upon coming together. As the design process continued, each connection to these inaugural makers stretches the link span.

When reproducing the number of links by link span, a subtle difference between the teams signaled different patterns of regulation in design (Figure 19). Though both teams had a large link span, these distributions were skewed such that few links had a large span. The links extracted from Evan and Fiona's design process tended to be closer together than those in Sydney and Jordyn's design process. In other words, though a number of links were created, they were densely organized rather than integrative. Evan and Fiona's comments were succinct and their responses mainly took in recent information, forming shallow, connecting webs.

A depiction of the design link directions by time also supports the claim that first days were foundational (Figure 20). By definition there are fewer backlinks at the beginning of the process and fewer forelinks at the end of the process. However, there are many forelinks to begin, indicating that early links were highly referenced later on. For Sydney and Jordyn, an expansion of forelinks around move 300 corresponds to backlinks at move 600—the fabrication and hypotheses, and then testing, evaluation, and self-reactions. At move 1,000 the team began to catch up on documentation in engineering design journals, and completed a self-assessment

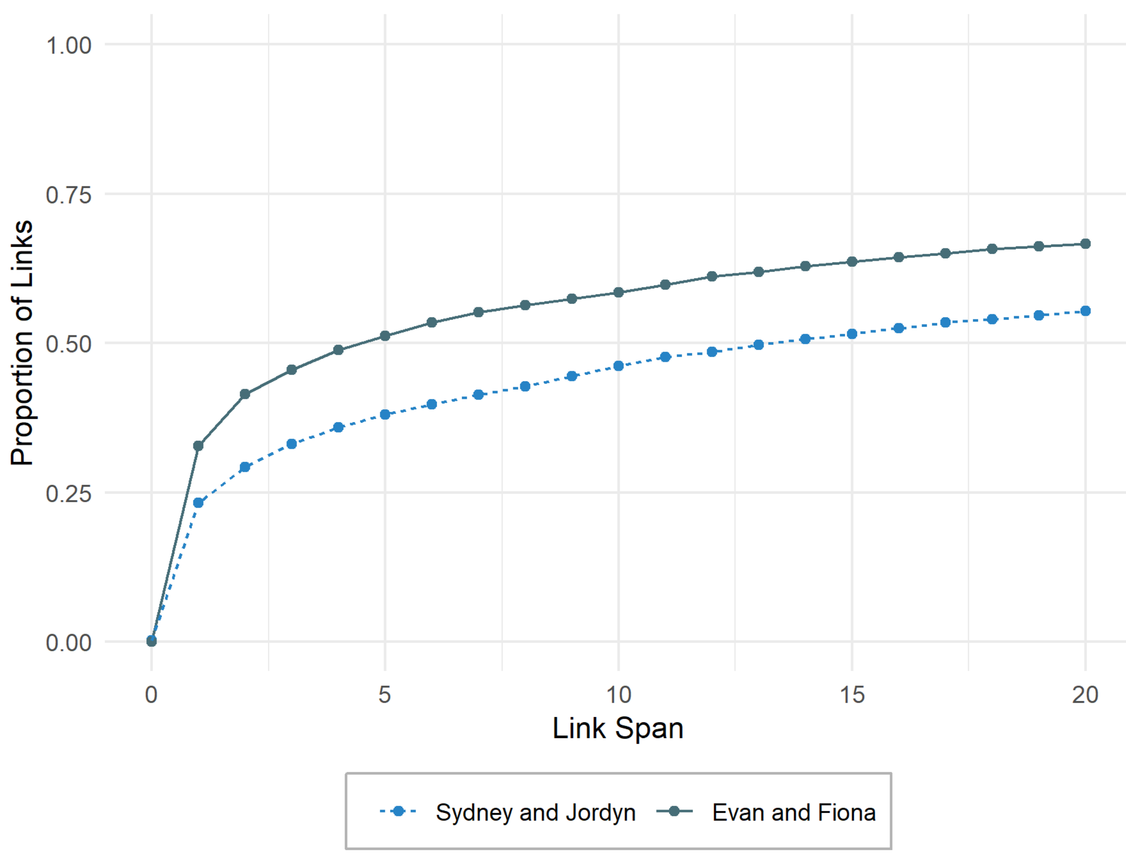


Figure 19. Link span diagram indicating the proximity of connections made by design teams.

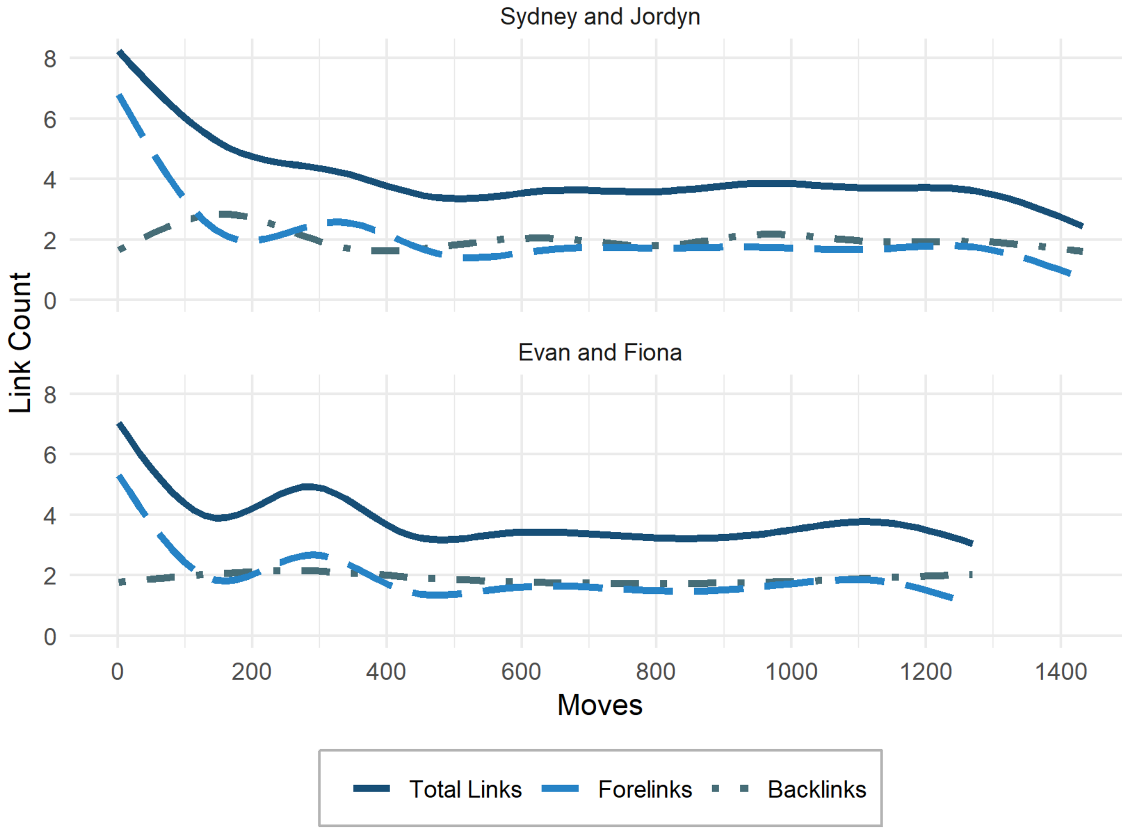


Figure 20. Smoothed link count by time and direction for design teams.

prescribed by the teacher, leading to reflective backlinks as demonstrated in the representations. A final swell in forelinks after move 1,200 shows a push toward the final design attempt as the team began making a backup mold. For Evan and Fiona, there is a similar increase in forelinks as the team finalized their ideas. The shift towards evaluation is not as evident, though there is an upward trend for forelinks originating as their final test was conducted, around move 1,100. Some of these episodes are illustrated later on.

The directionality of the links among teams was comparable (Table 7). Most moves had links in both directions (about the two-thirds ratio seen elsewhere; Blom et al., 2018; Goldschmidt, 2014). Of unidirectional moves, most had a backlink only and fewer had forelinks only. Most of the ideas given by a team were based on past ideas, and further discussed while working. Only a few moves, 1.7% for Sydney and Jordyn and 0.7% for Evan and Fiona, were not linked. These tended to be ephemeral statements like, “this is going to blow up like a balloon animal,” without further response by either team member.

Moves generated by each team were not evenly distributed by day, nor were they linked evenly by day (Table 8). The first days of class were a sense-making process, becoming oriented to the design challenge. A lower move count and higher link index for Sydney and Jordyn's first day is suggestive of this tentative, individual exploration. As previously mentioned, this first day included foundational instruction which was built upon day by day by the instructor. It was also build upon immediately as the team united and began working together, explaining the high number of links between Day 2 and Day 1. Later days connected most heavily to this first day, and the day just prior. This suggests that information cascaded from day to day, but had revisions in the course of the process. For example, on Day 3, Sydney and Jordyn did prototype testing of soft robot fingers, and exhibited links back to their design configurations and predictions of success on Day 2. Therefore, links were made to the most recent version, as it represented a culmination of work up to that point (Hatcher et al., 2018).

Before giving the overall linkographic representation and describing specific episodes, I look at the anchors in the process—critical moves. The specification of critical moves is also contextualized and flexible, based on the number of moves in the overall process; with greater

Table 8. *Daily Moves, Links, and Relationships by Design Team*

			Links Between Days				
Day	Moves	Index	1	2	3	4	5
			Sydney + Jordyn				
1	105	2.30	241				
2	407	1.71	160	698			
3	345	1.33	39	161	458		
4	252	1.48	16	54	80	374	
5	324	1.60	1	12	29	49	517
			Evan + Fiona				
1	136	1.84	250				
2	164	1.37	127	225			
3	316	1.57	44	81	496		
4	411	1.49	10	8	90	612	
5	242	1.64	17	6	14	34	398

moves are increased opportunities for connection. Therefore, Goldschmidt (2014) recommended an exploratory process that set a threshold around 10% (p. 58). Thresholds are denoted for the direction and threshold number of moves: for example, "<CM^4" is a backward critical move for having at least four connections to prior design steps. The number and proportion of critical moves, by direction, are supplied in Table 9. Sydney and Jordyn had more critical backlinks, suggesting a more reflective process overall. Furthermore, the number of critical moves captured at these thresholds was smaller for Evan and Fiona, meaning fewer links were frequently referenced throughout the design process.

Due to the large number of moves, the thresholds set still present too many moves to analyze. However, the distribution of critical moves by time is shown to suggest the structure of thinking, overlaid with design testing outcomes—green for successes and red for failures (Figure 21). Sydney and Jordyn's process varied alternately between forward-facing and backward-facing critical moves. Significantly, the test outcomes appeared as critical moves for Sydney and Jordyn. Each finger test result was included at <CM^4, signifying that the finger design and test results were associated with team intentions; conversations about planning and design variables were compacted into the finger design and testing. All of their test results, successful or not, were included at CM^4> for the flurry of evaluation and reaction that took place afterwards. The test outcomes for Evan and Fiona were not included in their forward critical moves, showing a disconnect between planning and fabrication. On the other hand, nearly all of their test outcomes had implications for future moves. In the outlier instance, when their second finger inflated and immediately failed, the momentary success was not referenced later on.

Table 9. *Critical Move Count and Proportion by Direction and Threshold.*

Design Team	CM^4		CM^5		CM^6	
	Backlink	Forelink	Backlink	Forelink	Backlink	Forelink
Sydney + Jordyn	140 (9.8%)	213 (14.9%)	53 (3.7%)	149 (10.4%)	20 (1.4%)	109 (7.6%)
Evan + Fiona	69 (5.4%)	166 (13.1%)	16 (1.3%)	99 (7.8%)	9 (0.7%)	70 (5.5%)

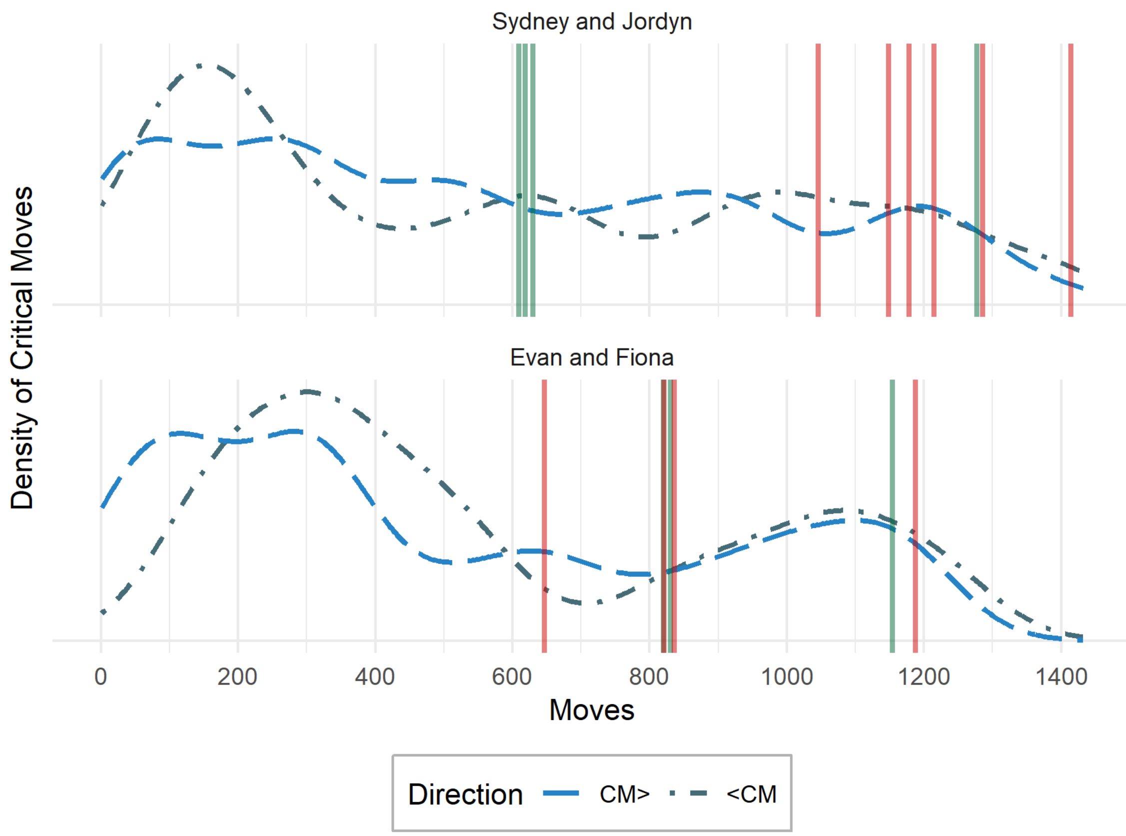


Figure 21. Critical move distribution, overlaid with design test outcomes. Testing outcomes are failures (red) or successes (green) and are aligned by design move.

4.2.2 Identified Patterns in Linkography

As recounted in the design chronologies and alluded to in the previous discussion on linkographic patterns, the nature of the soft robot experience can be discerned from the linkographic representations. The linkographic representation of each team's process looks tangled due to the large number of moves and links, and the large span of many links. A representation of Sydney and Jordyn's process is shown in Figure 22. A representation of Evan and Fiona's work is shown in Figure 23. However, from studying the figures, an underlying structure is manifest. I call attention to further patterns of self-regulation and response to failure in the following figures. While some of these features have been described in the previous design chronologies, the visual depiction of these patterns, coupled with closer description of the design process, is informative.

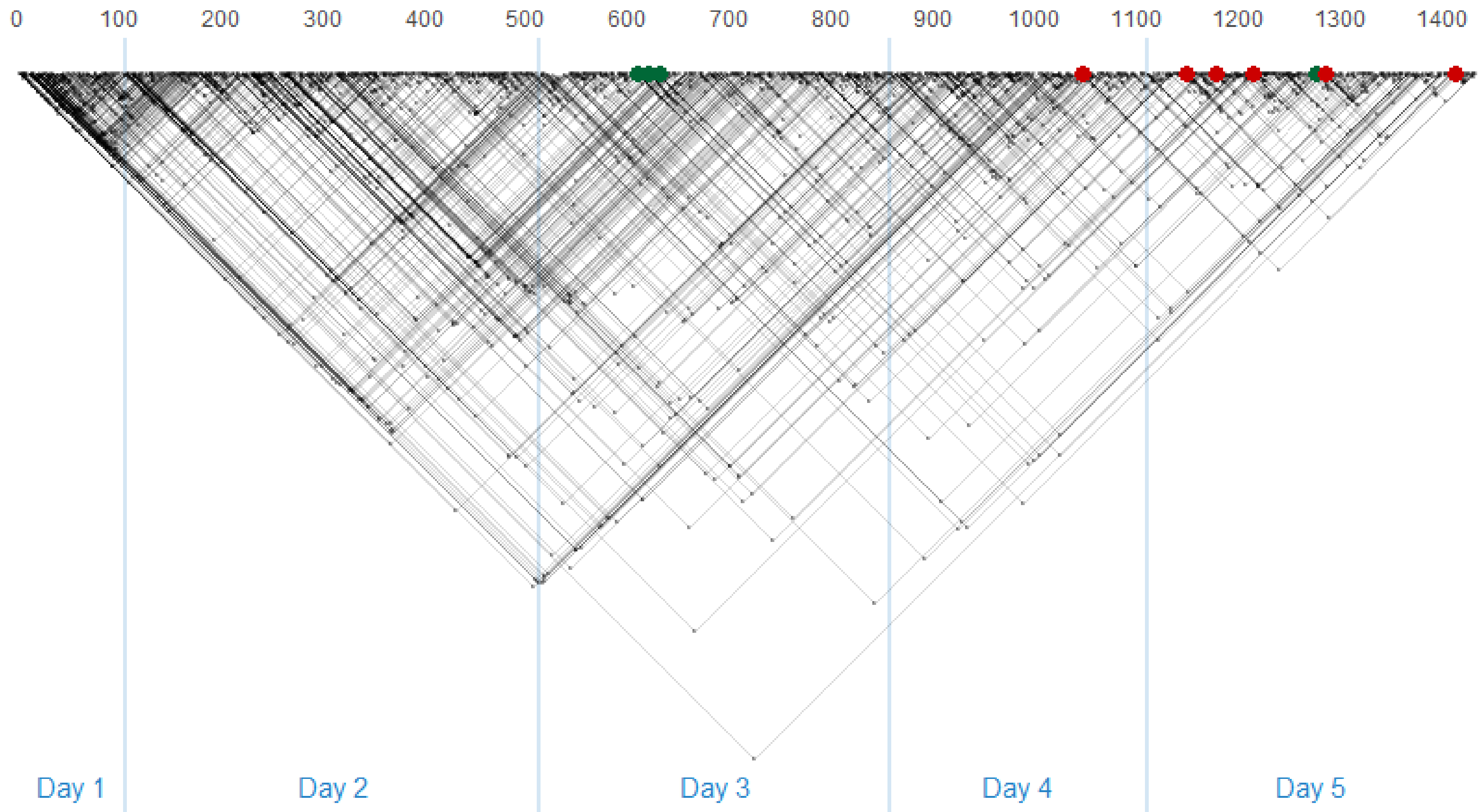


Figure 22. Linkograph of Sydney and Jordyn's design process over five days. Design testing outcomes are shown as failures (red) or successes (green) along the design moves.

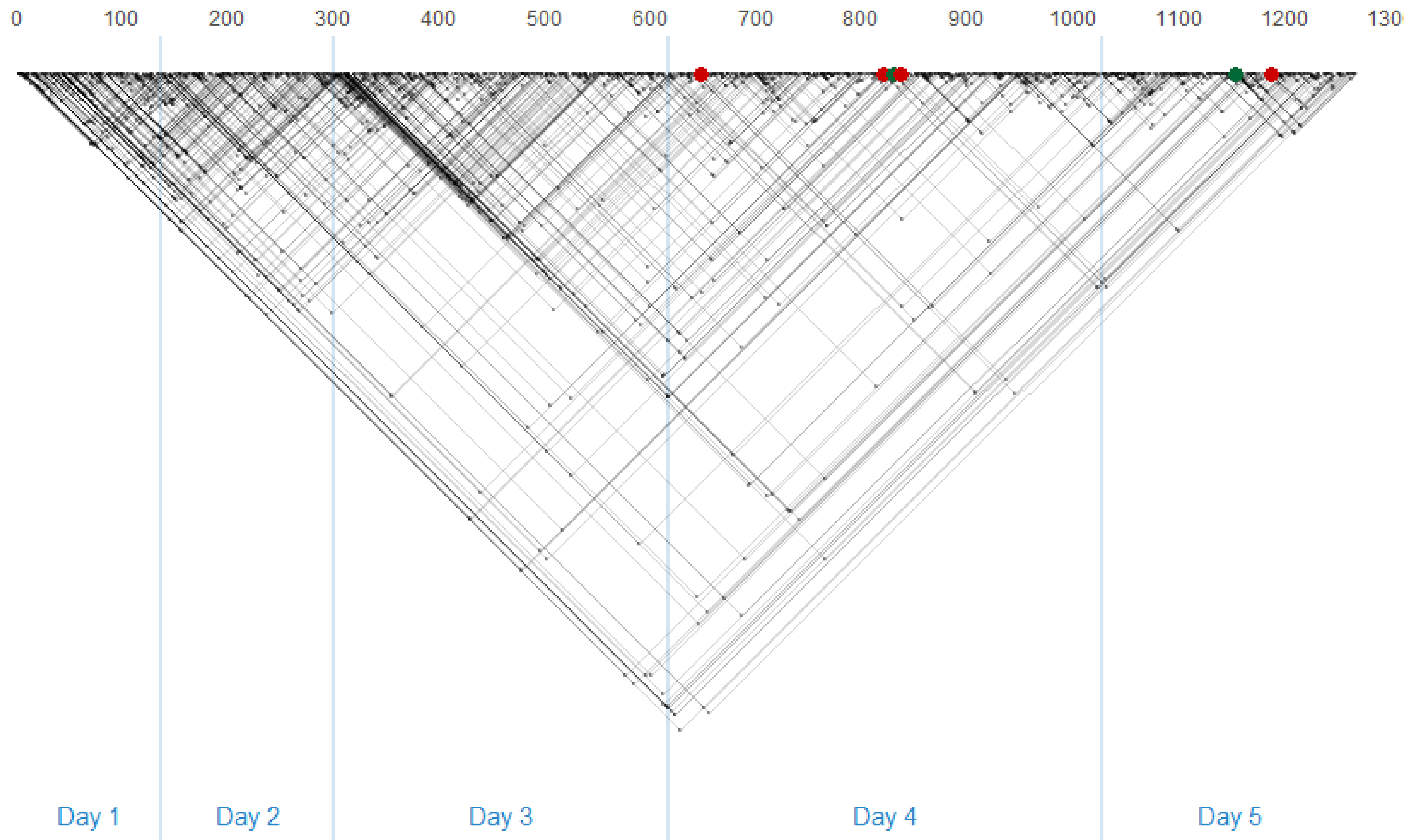


Figure 23. Linkograph of Evan and Fiona’s design process over five days. Design testing outcomes are shown as failures (red) or successes (green) along the design moves.

In the linkographic diagrams, forelinks and backlinks depict forethought and reflection, and can be disambiguated to infer subcomponents of self-regulation. For several features of the representations, the connections between linkographic evidence and self-regulation theory are discussed. Each of these features shows my interpretation of the design experience and self-regulation practices of beginning designers.

There was a foundational beginning to the design process for each design team, showing forethought in self-regulation. The interconnected nature of these moves was alluded to in Table 8 and Figures 20 and 21. Focus on the conceptual design phase, preceding any fabrication by teams, showed a concentration of links as teams set goals, discussed expectations for the project and their brainstormed ideas, and planned strategically (Figure 24). This phase was more efficient for Sydney and Jordyn than for Evan and Fiona; Sydney and Jordyn had a higher link index (Table 8), showing the density of planning and reflection, and moved from conceptual design sooner than for Evan and Fiona. Sydney and Jordyn had more iterations later in their design, which may also be related to the beginning of design process—they planned and started early, leaving time for adaptations in their approach.

Part of the day-to-day structure of the design experience was led by the teachers, who reiterated broad goals and fabrication guidelines. These aims were instantiated on Day 1, as part of the conceptual design phase just discussed, but extended daily to evolve in parallel to the design process. For example, on Day 3, Mr. Gray shared, "You're going to design, test, and create multiple ideas for your fingers…. So you can do fingers, based on those fingers you're going to make a hand. Based on the test of the hand, you'll make another hand." This statement reflected goal setting, as an element of self-regulation. His comments were followed by encouragement to begin fabrication and a demonstration for students who had not yet planned their fabrication process. Since this instruction was the first formal explanation of fabrication for Evan and Fiona and it was concentrated in time, the pattern of reflection back to fabrication steps is evident in their design process. These fabrication instructions were especially connected to later ideas (*Figure 25*). Important points such as this were helpful for student forethought in design, and were reflected on throughout the remainder of the experience—both as students began to make individual finger designs, as well as when they completed their entire gripper design.

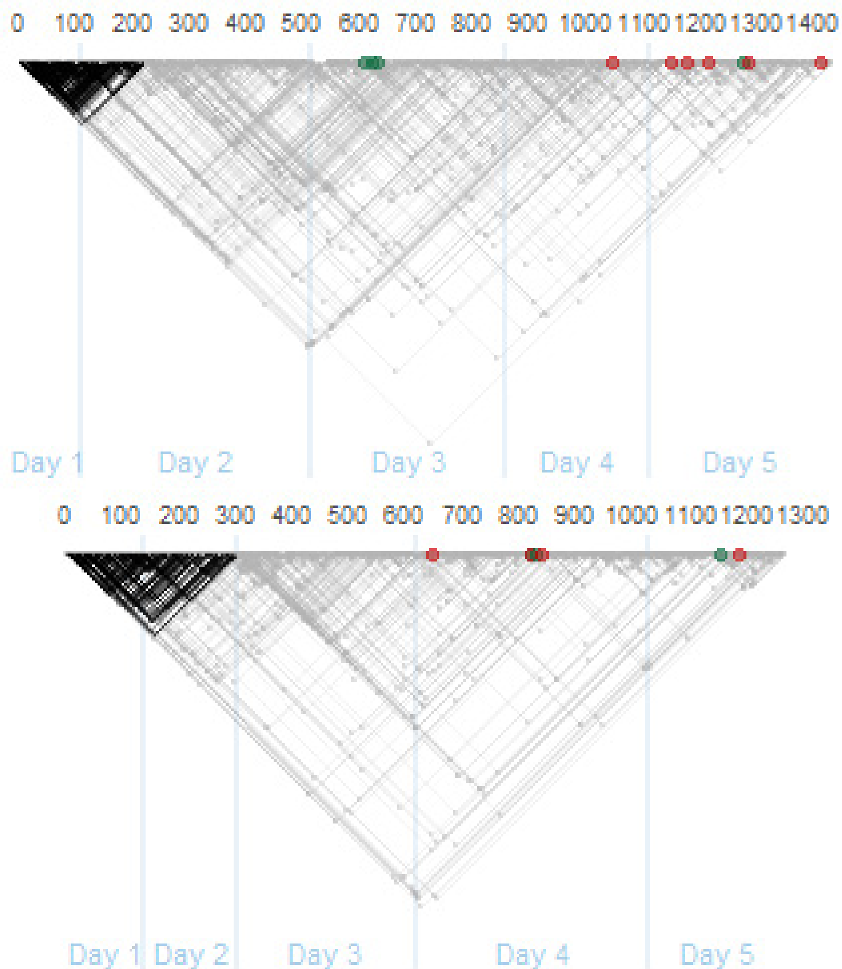


Figure 24. Emphasized linkographs for both design teams showing conceptual design phase. The linkograph for Sydney and Jordyn (top) shows a more efficient conceptual design phases than for Evan and Fiona (bottom)

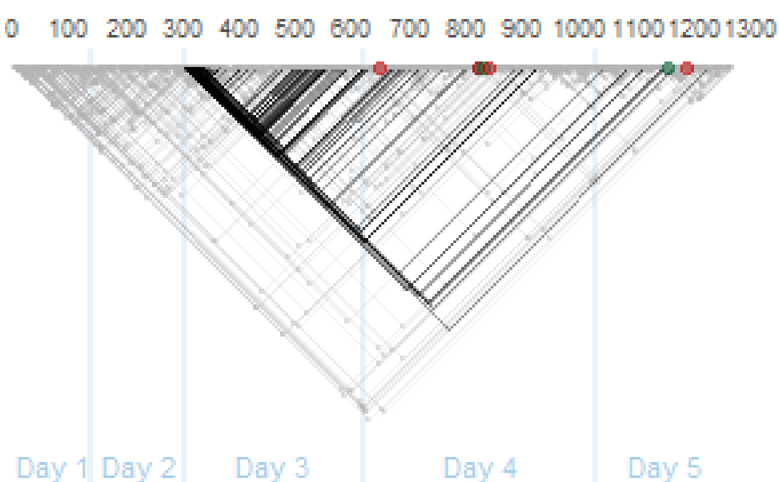


Figure 25. Emphasized linkograph (Evan and Fiona) showing forethought from instructions.

Other critical, and reflected upon, ideas included the use of design variables to configure and evaluate design tests. The linkograph diagrams provide a clear representation of when Sydney and Jordyn configured three different fingers and discussed the merit of each finger after testing (Figure 26). These were fabricated and tested successfully; then their conversation shifted to reflection. Their discourse referred back to the configuration of the designs and tried to attribute variation in performance to the variation of designs that had been strategically planned. A portion of their conversation, annotated with design move numbers in brackets, gives context to this evaluative discussion.

Sydney:	[634]	So it might… the more joints might help to get around the objects.
	[635]	You can test the smaller one again if you want.
Jordyn:	[636]	All right, retesting the smallest one so we can compare it to the longer one.
	[637]	I kind of like this one, in that it has three joints.
Sydney:		Mmhmm.
Jordyn:	[638]	But I feel like it needs to be longer as well.
	[639]	And I also… I like this gap right here.
Sydney:	[640]	Yeah, I think that our spacing was spot on with leaving the gap towards the center.
Jordyn:	[641]	Yeah, exactly. So I think maybe like the length of the middle one.

This evaluation also represented a pivot towards the design of their gripper, and another cycle of iteration and self-regulation.

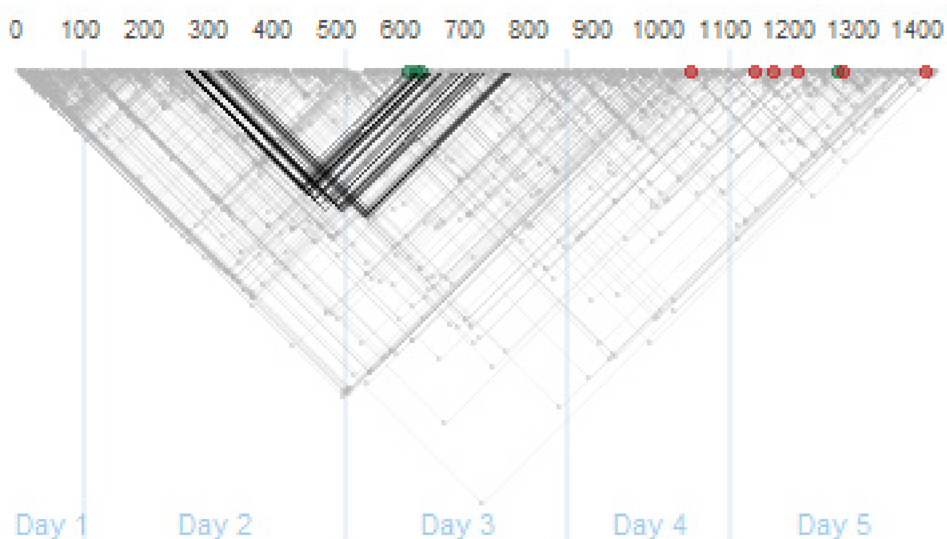


Figure 26. Emphasized linkograph (Sydney and Jordyn) of design planning and evaluation.

Finally, I identified a pattern within students' self-regulation pertaining to reflection and evaluation. Structure in the classroom and design process induced reflection, beyond moments of design failure or success. Specifically, design documentation was a common catalyst for reflection. The process of documentation was concentrated in downtime during the fabrication process. Therefore, the students' reflective thinking spanned back over the fabrication steps taken up to that point. As Evan and Fiona decided to move on from their gripper attempt and complete documentation, feeling successful in their design, a flow of backlinks ensued (Figure 27). These links turn back to the initial goals and criteria identified (at the beginning of the design process), and the configuration and test results of their fingers (intermediate in the design process) and gripper (in the end of the design process). In this way, their synopsis of the design process referred back to the beginning and end of each iterative, self-regulatory cycle.

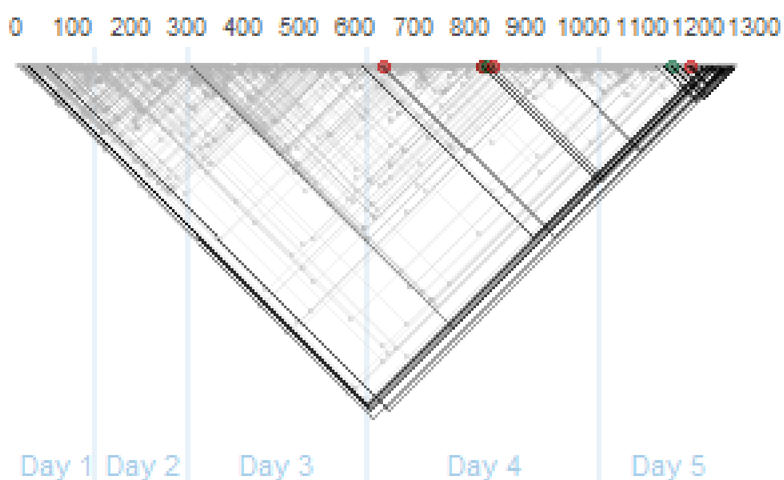


Figure 27. Emphasized linkograph (Evan and Fiona) showing induced reflection.

4.2.3 Summary and Implications

The linkographic analysis renders the design process quantitatively and qualitatively, illustrating significant touchstones in design and patterns of behavior. Especially spanning many days, the design process included much information to manage and incorporate for students. The beginning of the design process proved foundational, as evidenced by the visual depiction and counts of moves and links for each team. As teams proceeded to design, they were scaffolded by daily updates from the instructor, who shared relevant objectives and tips. Another milestone was Mr. Gray's formal presentation of fabrication steps, which was referred to later on by both teams. Furthermore, beyond the social contexts, environmental cues (such as a legacy of using the engineering design process and requirements to use engineering documentation) trained reflective behavior among beginning designers. Though documentation was completed to varying degrees, the documentation process was important to provoke reflection when it may not have otherwise occurred.

Despite having a similar link index and large link spans, the process of each team was differentiated by the oscillation between forethought and reflection, seen for Sydney and Jordyn, and the straightforward process of Evan and Fiona. The later team had fewer forelink critical moves, for strategizing and goal setting. The testing outcomes for Evan and Fiona were also postponed and concentrated, such that there was little time left to recoup afterward.

Students' responses to success and failure in design were also contextualized and different—by the timeliness of these experiences and how they were framed. For Evan and Fiona, even momentary success was referenced later on. Success of the team's desired finger design was satisfactory to fix this design as the chosen solution; and the initial inflation and short-lived ability to grasp an object were taken as an overall accomplishment in the design process. A contradiction in their process was the immediate failure of a finger, which was perhaps overshadowed by the results of their favorite design. For Sydney and Jordyn, the repeated failure of their grippers led to determination and repeated chunks of interconnected design moves. In these ways—the imposition of the classroom, multi-day structure on the behavioral patterns of the team; the social influence; and the environmental resources used for design and regulation—the linkographic analysis supports the claim that both design, and self-regulation in design, are contextualized.

4.3 Typological Analysis

To examine beginning designers' practice of self-regulation elements more specifically, typological codes were applied to the transcripts of each design team, follow-up interviews, and the design journals. The nature of the observations and data analyzed led to several patterns in the application of codes. First, with the dialogical focus on fabrication, codes were mixed in with directed conversation about the current fabrication step that remained uncoded; hence, the codes were scattered throughout the transcripts and files, rather than densely applied. Second, when divided by self-regulation phase, the predetermined codes yielded fewer performance phase elements. This difference was triggered by having fewer predetermined codes than forethought or self-reflection phases from the outset, as well as the difficulty of dividing performance from planning and reflection in the data. Therefore, examples of systematically changing design variables to test performance, which aligns with the definition of self-experimentation in the performance phase, was most often coded as strategic planning, in the forethought phase. And third, the classroom structure was again brought to bear on the data, leading to a possibility for duplicated coding of the teachers' instructions. Because two teams were in each classroom, day-to-day instruction was captured in both transcripts. To reduce focus on teacher modeling, the class-wide conversation was only coded for one team in each class.

From the coded collection of quotes, I extract a profile of how self-regulation subprocesses play out in the design performance of beginning designers. First, I discuss patterns within each of the three phases of self-regulation—forethought, performance, and self-reflection. Each profile is heterogeneous, adding breadth to the display of self-regulation. Following a discussion of each profile, I synthesize self-regulatory elements and the design process, showing an alignment between design and self-regulation and that cyclical phases in design can be executed as a microcosm of the larger design and self-regulation process.

4.3.1 Forethought in Design Self-Regulation

Self-regulation begins with forethought, planning and framing in advance of performance. Codes in the forethought phase of self-regulation, as enacted by these designers, were grouped into four themes:

1. Goal setting and planning,
2. Goal visualization,
3. Forethought to transition information from previous attempts to future attempts, and
4. Psychological framing for future attempts.

Collectively, these themes instantiated a new cycle or iteration in design, and propelled the design forward.

4.3.1.1 <u>Characterizing Goals in Design</u>

There was a polarity of timeframes in goal setting with goals established long- or short-term. For example, introductory comments from the teacher setting goals for a day or more.

These distal goals established a trajectory for several days and served as a reminder to teams of the particular tasks on which to focus. Mrs. Childs often began or ended her class with a statement to the effect of, "I want to get a feel for where we are and where we're headed." Team comments also spoke broadly to establish a sequence for iterations and final design.

> Fiona: I thought we were just building a hand, right? Isn't that what we're doing?
> Evan: Well, we have to design a finger.
> Fiona: Well, we only just design a finger, like that mold?
> Evan: Yeah, and then we just build four of those fingers.

More proximal goals in the design process oriented the team to next steps, especially for fabrication, and ensured continual progress toward the distal goals of design. Wes stated, "Basically, all I'm doing is putting the pieces in and then I've got to fill them with the silicone mixture" to orient himself on adding clips to his mold, and the next step of adding silicone. Evan asked a similarly purposed question to his partner, "You read all the directions. What are we doing next?" Variety in the timing of goals meant that they occurred throughout the design process, not just at the beginning of design; each transition represented an opportunity for goal setting and accountability.

Goal statements also emerged from several sources in the course of soft robot design. Daily objectives from the teacher were internalized by students as goals to achieve. On Day 2 of their design work, Sydney and Jordyn asked for some context about project timing. Mr. Gray told Sydney and Jordyn that they would be working on the project for several more days, outlining some possible milestones for each day.

> Mr. Gray: Around how long... as in how many days? Today is day 2 and we're just starting to test fingers. Um... you could possibly design a second set of fingers. But you wouldn't be able to cure it and have it ready tomorrow. You do that one tomorrow and after that you do a hand. Which is Wednesday. So we're thinking definitely through Thursday. Actually probably all the way through Friday.

They followed up soon after by affirming their intent to "at least be able to get the fingers out of the molds" (Sydney) that day, and keep ahead of schedule.

Two steps in the design documentation requirements also translated clearly to goal setting, and later evaluation processes. As students began their documentation they were to "define the problem" by writing specific details of who, what, and why. Step 4 of the design process, to identify constraints and criteria, also asked students to write "what you want to accomplish" (class handout). Snippets of conversation as problem statements and constraints and criteria were defined and documented, illustrate students' approaches to goal setting:

Jordyn:	The class needs to develop a soft robotic hand that is able to pick up and hold materials. (written)
Fiona:	Step 1. Define the problem. What is the problem?
Evan:	The problem is… is that we need to build a robotic hand to pick up multiple objects without damaging them.
Katelyn:	Criteria/Constraints: Must be able to pick up a variety of objects. Must be able to hold the object for 5 seconds. Must be able to release object by opening the air valve. (written)
Wes:	So what did you put as the problem?
Taylor:	I said that we are to make a gripper that can like… to make a hand to grab an object.

Mr. Gray and Mrs. Childs both emphasized the redesign aspects of the soft robot design challenge, and that failure was a learning opportunity. They emphasized to try a variety of ideas, not to rush, to think about their final design, to make decisions informed by research and testing. With one exception, attempts to reinforce mastery goal orientations came from the teacher or after the fact (in my follow-up interview). These attitudes were only taken up by Sydney and Jordyn in their dialog, usually to mitigate the impacts of a potential failure. When preparing an idea, for example, Sydney said, "We can go with that. I mean, worst comes to worst we can fix it, change it, …rearrange it." They accepted in advance that their soft robot fingers were testing, to "help with the actual project" (Sydney) and inform them about design variable impacts.

4.3.1.2 Goal Visualization

Inspiration for design teams' goals came from teachers' statements, such as those mentioned above, as well as their research, first ideas, and beginning steps in design. The project was unfamiliar at first, and while the end result of a finger or gripper was clear, students "didn't really understand what [the] process was going to be to make the finger" (Fiona). This inexperience had ramifications for design performance and evaluation. As Fiona put it, "How can I make pluses and minuses [evaluate an idea] when I've never done this before so I don't really know." Upon beginning design work, especially handling mold parts and seeing visual representations of other soft grippers from research, understanding of goals solidified. Many teams developed an analogy between human hand structures and the soft grippers, to foster understanding. In the follow-up interview, Sydney said for her team, "Ours was focused on a hand, like an actual human hand," and Fiona agreed stating, "That's what we did too. We tried to space it out how the joints are spaced out in your finger." Teams came to make assumptions about the curvature of soft grippers based on the design materials available, and decisions about how to execute the task. Expanding cycles in the design process lead to greater confidence in what to do, including information to shape future iterations.

4.3.1.3 Forethought as a Nexus for Improved Performance

One method by which forethought improved performance was the inclusion of variation in design testing, to see a range of results. Each team recognized opportunities to vary their design at different stages of the design process. These sticking points were referred to later on, when configuring the finger designs, and checked again when configuring the gripper attempts. While the design variables here are specific to the design of soft grippers, the conversational examples show methods of establishing variety in the design process. Designs were varied most by length, clip number, and clip spacing (see also Figure 28):

Katelyn: We should make a long finger, and then we should make a short finger, and then a medium finger. And see which one would curve the best.

Sydney: So how many joints do you think we should put in here?
Jordyn: Um, well this one has four. So maybe we could do five in that one and then three in this one?

Wes: For our first brainstorm I wanted to create a finger that at the very tip it would have one [clip] and it would increase. So it'd go one clip, two clips, three clips.

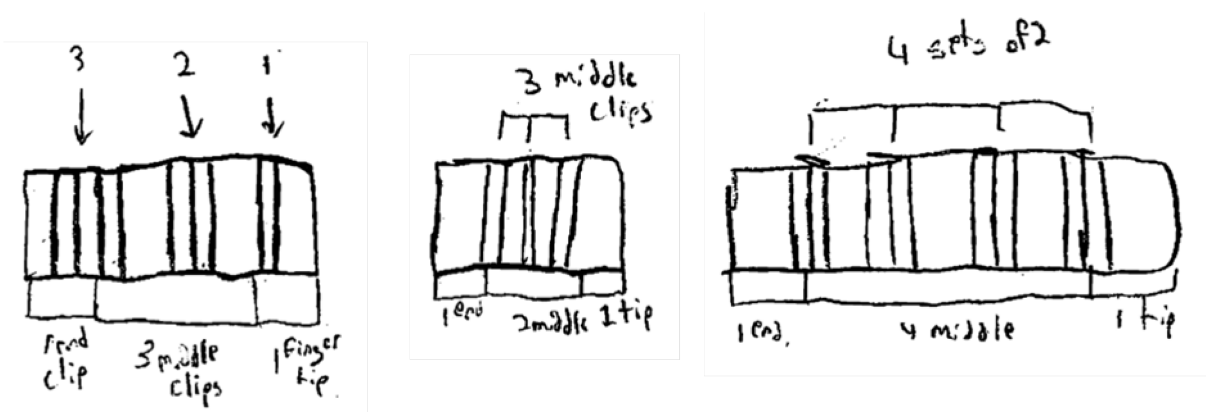


Figure 28. Documented brainstorming of finger designs with varied clip spacing. Drawing from a design journal shows three possible configurations: three clips, then two clips, then one clip together (left); three clips in the middle of the finger (middle); and four sets of two clips in a finger (right).

In addition to inserting variety into design, the strategic planning code represented the connection between past evaluation and future performance. Once teams started the process, acquiring information, they were able to shape their next steps with greater confidence. Brynn said:

> We used [the best design] and… we based it off of each one. Once we started, once we did our first finger and we figured out what was wrong with that, then we went on to the next one to try to see if we could do something different to make that one better. Or to be more careful about the next one.

Design teams based their future behavior on what had worked well in the past—for example, Katelyn asked Brynn to mix silicone because she had done it previously with success—or what had not worked well—Sydney put on gloves because her hands had been gross the day before, and while some gripper attempts were curing, Sydney and Jordyn made several backup molds "in case we decide to make another hand" (Jordyn). Furthermore, predictions of success, outcome expectations, impacted performance and decision making. Without past experience in the realm of soft robots, students made inferences and predictions and chose what they expected to work. These examples demonstrate how information cascaded forward in the design and self-regulation process from both success and failure.

Classroom expectations for repeated soft robot finger designs, and the sequence of conceptual design before fabrication, supported student planning. In instances without planning, the collaborative nature of the design experience often mitigated the negative impacts; team members checked one another's understanding before proceeding. For example, when Brynn was ready to retrieve silicone for mixing, Katelyn asked "Do you know how much you're getting?" before addressing it as a team. Still, the lack of planning could introduce problems that similarly carried through design. When making silicone to attach fabric, Evan said, "All right, I'm mixing it then. How do I mix this?" He started without understanding to stir gently, and created numerous air bubbles in the mixture; his attempts to remove the bubbles were unfruitful.

> Evan: Well I tried mixing it and it made a bunch of bubbles.
> Fiona: There's literally so many bubbles in here now. Oh, dude they are not going away.
> Evan: I know.
> Fiona: What did you do?
> Evan: I didn't do anything.
> Fiona: Why were you aggressively stabbing it?
> Evan: I was trying to pop the bubbles.

Fiona: Okay. We have learned when the instructions say to gently stir the silicone, you need to gently stir the silicone.

Evan: Did it say gently? Where? I don't know why you're expecting it to say gently. Yeah. Fiona, we learned the hard way.

The team recognized the potential risks of air bubbles making it so the "air won't stay" (Fiona) and having acted without planning. The problem did not emerge in reflection on the finger designs, though Evan and Fiona were more attentive to air bubbles the next time they made a silicone mixture.

4.3.1.4 Psychological Framing

The impact of forethought goals and strategic planning, on design performance was expected to be moderated by psychological elements of forethought: self-efficacy, intrinsic interest and value, outcome expectations, and goal orientations. Goal orientations and outcome expectations were touched on in the earlier discussion of forethought. The novel context and materials of the soft robot design experience piqued students' interest in the project. At various times they uttered that it was an interesting project because "it was a lot different than something we had done before…it was a different material… a little different concept" (Jordyn) On the other hand, statements like, "I don't want to do this" (Fiona) were also made. On the part of self-efficacy, students' framing of the experience tended toward the negative aspects such as past failed attempts or negative outcome expectations. They recognized that as the fabrication process developed, it was "definitely going to be more difficult with having the whole [gripper] to seal and cure, instead of just having the… fingers" (Sydney). Regardless of interest or confidence, students continued in the project. It is possible that motivation was externally regulated by the educational setting this experience took place in. Therefore, the precise impacts of confidence and interest in students' reactions to success or failure are unclear.

4.3.2 Performance in Design Self-Regulation

Less information was evident about how students regulated performance during design, the self-regulatory phase following forethought, though what was found corresponds with extant literature about regulatory task strategies. Two themes related to performance regulation:

1. Regulatory task strategies, and
2. Design documentation as a self-record.

A variety of task strategies are considered helpful including drawing or summarization, information searching, time management, and help seeking (Azevedo & Cromley, 2004). Examples of each task strategy are given in turn. Considering the design journal as an evolving record of design, the documentation process also has potential to inform self-regulation in design. I share limited insight into the utility of documentation to establish and maintain design trajectories.

4.3.2.1 Task Strategies in Performance

Students used drawing and summarization to offload memory and record their progress. Therefore, students' drawings corresponded to the design journaling and self-recording tasks described next. Documentation seemed primarily to satisfy the documentation requirements for their classes, though students disagreed about the extent of documentation required. Drawing, when coupled with summarization, was used to support individual understanding.

> Brynn: Finish writing it? Oh, you drew, too? I didn't do that.
> Katelyn: I'm visual.
> Brynn: I'm more of a written… I don't even know.
> Katelyn: If I just wrote it I wouldn't really understand.

Katelyn's self-awareness shaped her use of task strategies to build understanding and record her work. Another interesting use of drawing was to communicate understanding between design partners. Jordyn began discussing an idea about clip spacing, before saying, "Here, let me draw the cross thing [gripper] so you can tell what I'm talking about."

Research was also used to check understanding and inform the process. Fiona said, "When I researched I was able to see step-by-step what we were doing. And once I figured out what we were doing, it made it easier to understand the actual outcome of the project." Fiona's tactics for research were vague information searches, which led to advanced websites that she struggled to decipher. However, Sydney's tactics for research focused on visual representations of grippers that helped in goal visualization:

> I kind of know what I'm looking at. So I think I'm gonna do pictures for this step because they already showed us how to do it. So I don't really need to look it up…. A lot of these grippers I'm finding look much more advanced than what we're doing. But these pictures are making me thing maybe I should have more joints in my brainstorming.

Curing soft robots is time dependent, which likely stimulated time management strategies undertaken by the students. The process was constrained with minimum times for curing, 15 minutes in a toaster oven or 4 hours at room temperature. Therefore, students had these times in mind and frequently checked the time left in class to determine how to proceed. As discussed previously, this led to lackadaisical behavior when students perceived too little remaining time. On the other hand, it also led to hurried pacing when trying to meet an end-of-class deadline.

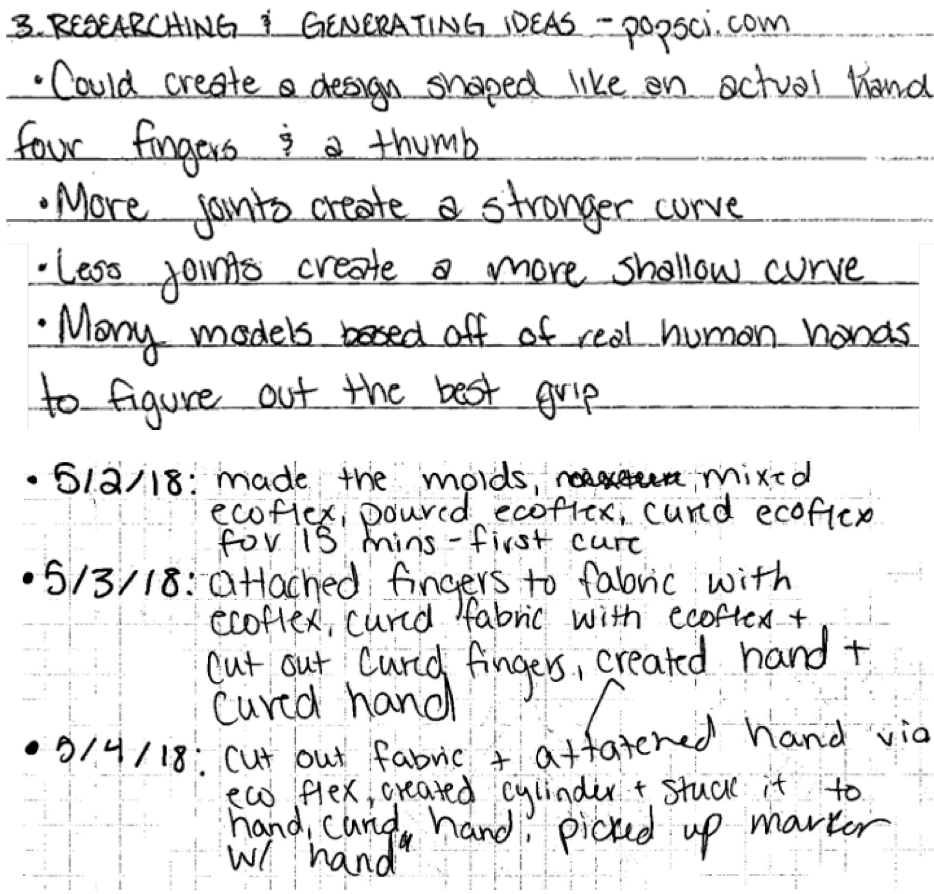
Teams also showed different comfort with help seeking or questioning throughout the process. Brynn and Katelyn readily asked questions, even with the teacher's notice to use other resources first. Their questions were usually answered by the teacher or peers.

4.3.2.2 Recording Performance

Sometimes task strategies and the process of self-recording intersected to support students' regulation in design. Examples include the use of drawings and summaries in design journals, recording research to identify new insights, and keeping a time record of day to day activities in journals (Figure 29). While there were many consistencies in the design journals, especially by class, individuals did customize their documentation to support self-recording. Evan's journal was sparse, Fiona argued it was too limited to be useful. Fiona included detailed drawings in her journal, with a side comment noting that the drawings were hypothetical because the team's gripper had been destroyed. Sydney included the calculations for silicone to make the gripper; Katelyn included the total of each part next to her final drawing. Each student did include a form of decision matrix in their journal to aid in selecting an approach, as well as a table for conducting idea evaluations. I suspect this is due to documentation in the case context being close to what was done in the past, and students' familiarity with the requirements at that point in the semester.

Teacher provided resources, such as the step-by-step and measurement guide were instrumental in the fabrication process, as the teachers predicted they would be: Mrs. Childs handed it out with the message, "This paper is very important, you'll be referring to this all the time," and Mr. Gray said, "If you're not exactly sure what you're doing, just grab one of these packets and follow it. You do need to have one of these."

However, based on my own observed inconsistency in quality of design documentation, I questioned whether the records were referred to during the actual design process. I did see evidence of teams filling out the documentation iteratively, in lock-step with their design progress. Brynn and Katelyn agreed to "write the list of what we found from the one hand…and



3. RESEARCHING & GENERATING IDEAS - popsci.com
• Could create a design shaped like an actual hand, four fingers & a thumb
• More joints create a stronger curve
• Less joints create a more shallow curve
• Many models based off of real human hands to figure out the best grip

• 5/2/18: made the molds, mixed ecoflex, poured ecoflex, cured ecoflex for 15 mins - first cure
• 5/3/18: attached fingers to fabric with ecoflex, cured fabric with ecoflex + cut out cured fingers, created hand + cured hand
• 5/4/18: cut out fabric + attached hand via eco flex, created cylinder + stuck it to hand, cured hand, picked up marker w/ hand

Figure 29. Design journal excerpts for research (top) and daily record keeping (bottom).

then, the next time…we can do two" (Brynn). Teams did refer to their documentation to construct the desired design of their soft robot fingers.

> Fiona: How many [clips] do we use, six? Five or six?
> Evan: Count.
> Fiona: I'm pretty sure I wrote it down…. Six pieces, five joints.

And a few cases were seen where teams wrote what to do differently next time. However, in general, documentation was concentrated to periods at the end of cycles of designing and I did not see strong evidence of the design documents as interactive records used to shape future performance.

4.3.3 Self-Reflection in Design Self-Regulation

Next, I consider the final phase of self-regulation: self-reflection. Evaluations and attributions pertaining to success or failure are contained within self-reflection (Figure 9). While conducting thematic analysis of this design evidence, I was able to shift my conception of success and failure. I moved from a strict interpretation of design attempt results, used in linkography to select certain moments in design (moves), to a broader definition of success and failure that encompassed design testing results as well as processes (e.g., dealing with proximal goals in forethought phases or with impasses). The shift in conceptualization of failure aligned with the first theme in reflection about the frequency of evaluation. While comments on design failure modes are context specific, the means whereby students identify and interpret these failures are transferable and illustrate a range of evaluation and attribution seeking behaviors by design teams. From analysis of reflection in the design process, I found four themes:

1. The occurrence of intermediate evaluations throughout the design process,
2. Identification and context of failure modes,
3. Accumulation of information for iteration or ending design cycles, and
4. Reactions in the design process.

4.3.3.1 Intermediate Evaluations

While less formal than identification of failure modes, discussed next, intermediate evaluations took place throughout the design process. In contrast to brainstorming rules that suggest deferred judgment (Osborn, 1953), these statements were based on in situ evidence and often relayed to partners to shape performance in the moment. Examples included observations when spreading out silicone, “I feel like that’s pretty good, maybe a tiny bit right there” (Jordyn); impromptu reactions to ideas, “ours looks pretty solid if you wanted to know” (Brynn); or evaluation of brainstormed ideas, “I think we need to make it longer” (Wes). These were not prolonged moments. The design process steps of exploring possibilities and selecting an approach entail judgments before proceeding. Indeed, design is a divergent and convergent process (Goldschmidt, 2016). However, with the inexperience of designers, these judgments were often based on assumptions rather than tested results.

4.3.3.2 Identifying and Interpreting Failure

The design of soft robots required more precision than students imagined. Jordyn commented that small flaws ruined the project, even if everything else was fine. However, when designs did not work, the failure evoked further inspection and recognition of underlying issues.

I organized statements about failures or attributions into three areas—materials, process, or understanding—and quote or restate these in Table 10.

Most of the flaws were surprising for students, who expected them to be talked about beforehand. The mold-related issues were especially frustrating for students because of their unexpected and external nature. When reacting to clips rising up in the gripper that led to a ruptured top surface, Katelyn said, “Oh, that one would have been perfectly fine if the clips didn’t come up.” Once errors were observed, assumed causes from the fabrication process were identified and documented to inform next steps.

4.3.3.3 Accumulating Information to Iterate or Interrupt Design

In conjunction with forethought informing performance and reflection, the end states of self-regulation inform future cycles. Based on background information, intermediate evaluations, and identification and attribution of failures, students choose whether to change their soft robot designs or fabrication processes. Initially, configuration of the design was most variable; teams determined how to change their designs based on testing results. Evan said, “We had one [finger]

Table 10. *Identified Failure Modes in Materials, Processes, and Understanding.*

Materials	Processes	Understanding
“The clips floated up” (Wes) “It ended up exploding when we put it in the [oven]” (Jordyn; rubber bands broke) The mold “curls up” or is uneven (Brynn) “Silicone is falling through the [parts]” (Evan) “Maybe it’s just a bad mold” (Jordyn) Mold bending “because of the rubber bands tension on the ends of it” (Jordyn) “The latex rubber bands…affected our [gripper].” (Sydney; uncured silicone)	“Too much silicone so the air couldn’t get into each chamber” (Fiona) “[Air] leaking out of the fabric on the bottom” (Jordyn) “Didn’t mix their material 100%” so it didn’t cure (Mrs. Childs) Had an air bubble The silicone layer was laid down or sealed wrong Robot was “off of level” (Katelyn) or “knocked over” (Taylor) Uneven inflation (e.g., one finger doesn’t inflate as well) Silicone wasn’t spread evenly Spilled silicone	“I felt like I didn’t know as much about it as the other projects” (Sydney) “We did not listen to instructions apparently” (Katelyn) Misunderstandings about the project “I don’t know what happened” (Fiona) – unable to identify failure mode

that was successful and the rest of them were varying. So we kind of just stuck with the one that worked." Moreover, individual responsibilities to complete a task were often unchanged in the hopes of maintaining success. For example, Katelyn asked her partner, "Can you mix the other solution? Because you did it last time and it worked out good." This sentiment was repeated by several teams while designing. As teams proceeded with their gripper, the fabrication process saw the most refinement; attributions of failure were associated with the process instead of the design.

Wes:	Oh, yeah. I see it. There's a hole. There's not enough….
Taylor:	Well, next time we can put more in. Ok, let's start our second one.
Evan:	Oh yeah, that is a lot of bubbles. Maybe we need to stir more gently.
Sydney:	I think we focused more on the changing of how we were executing the process rather than actually changing our design.

Each design journal included statements about the identified failures of the design. Extending this description, some design journals also included statements that translated evaluations of failure into next steps for designing and fabricating, arguably facilitating the next steps (Figure 30). I take statements such as these to incorporate both evaluative, and strategic planning elements, relating to themes observed in the forethought phase of self-regulation. It is from the evaluation and attribution of failures, and planned next steps, that iterative versions of design emerged. Yet, the failure experience necessarily preceded the evaluations, attributions, and iterations.

When developing soft robot fingers for testing, each team knew that the anticipated end point was a completed gripper, therefore there would be another round of fabrication. This was leveraged by some teams as an opportunity for experimentation, or a relief when ideas were expected not to work. In Brynn and Katelyn's account already shared, the two anticipated improvements as they iterated. Katelyn concluded, "the third one, the third one will be it," summarizing her feeling that the second finger was not going to be successful but that the third finger could be. Taken to an extreme, the lack of commitment when testing may be concerning, and cause students to overlook salient details or the potential for learning. When Fiona was trying to adjust a finger design, Evan told her, "These one's don't matter." The teacher also had to negotiate with the team to change their design when they expected it wouldn't work.

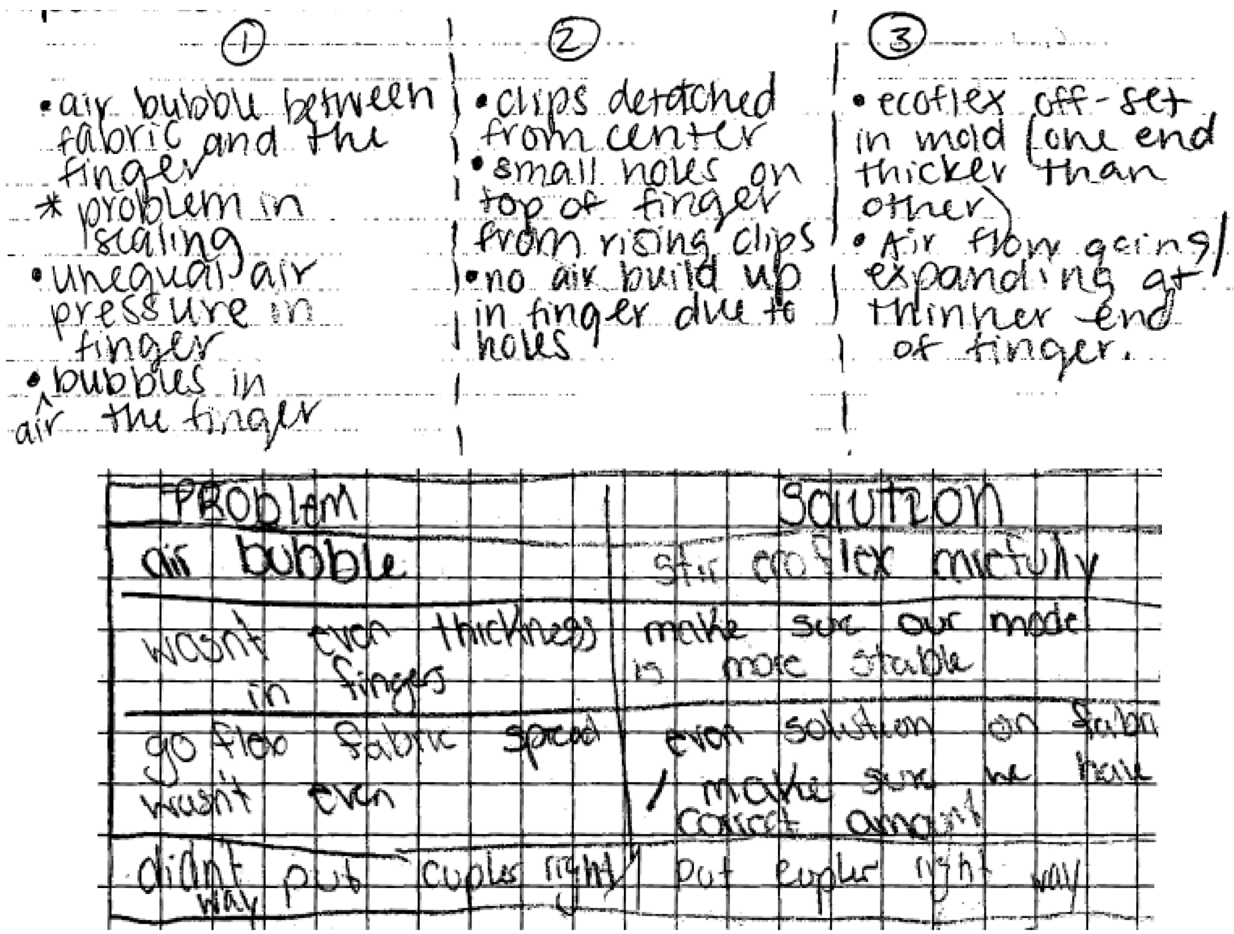


Figure 30. Two journal excerpts listing failure modes (top) and strategic planning (bottom).

Mr. Gray:	These [fingers] are to try a couple of different designs…. How well do you think this one's going to work?
Fiona:	I think that one's going to be [bad].
Evan:	Not at all.
Mr. Gray:	So why don't you change it so you might have a better chance of working, you know?

After the first gripper was completed and tested, it was up to each team to decide whether to create another gripper. Teachers had indicated this openness to redesign. Mrs. Childs told her class, "You're going to test it, see if it works, and decide how you want to change it or if you want to do the same one over again. Either decision is fine." Mr. Gray encouraged his class to redesign, but left it open:

> Based on the test of the hand, you'll make another hand. Even if the first one works well, you can always have it work better, right?... And after you test it, if you feel like one of the fingers is definitely going to work, them make a hand. If you feel like you're still not ready, make more fingers.

The chronologies show that most teams chose to iterate, though in different ways—some with repairs, some with new fabrication. Although, Evan and Fiona did not iterate in their gripper design, even once it had popped. Several experiences of teams choosing to iterate are given next, with commentary.

Iterating with External Attribution. Brynn and Katelyn's first gripper inflated partially, unevenly, and had a hole. Brynn was excited, seeking confirmation from Katelyn that the gripper worked. Every finger but one worked, which was documented satisfactorily. Katelyn added, "So now we're trying to make the fourth finger work too. Look at how cool!" The girls questioned why it was not working, and attempted to stretch and manipulate the robot, thinking that the air chambers were clogged. Then they saw and heard a hole in the top that triggered their attribution:

Katelyn: "Right there. Right where my finger's pointing. That air bubble.
Brynn: So we just have to be more careful with air bubbles."

The team deliberated briefly and decided to make another robot of the same design, focusing on process improvements. In this case, I believe the attribution of failure, that it was identified with a reasonable plan to overcome the obstacle in subsequent iterations, was influential in the team's decision to make another gripper.

Seemingly Futile Iteration. Wes and Taylor had begun making a second gripper and came to a juncture where they needed to decide whether to keep going or not. When removing the gripper from the first cure phase, they noticed floated clips cured in the top of the gripper. The team did not expect the gripper to be successful.

Wes: So, should we even make the coupler for this?
Taylor: Yeah, because it could work.
Wes: There's a holes in each of the fingers.
Taylor: Yeah, just do it anyways. I mean this is our last one. We're going to see if it works.

Nonetheless, they proceeded to make the robot and attempted to address the failure by covering the weak points with additional silicone. When they tested the gripper after adding fabric, there remained a hole in the top, which was covered and cured. The final test in class was hurried, but the robot was able to inflate unevenly, and I deemed it partly successful. In an earlier finger, Wes and Taylor had abandoned their approach because of holes in the top surface. Here, it is interesting that they chose to continue in the work, and ended up with a partly successful robot, exceeding expectations.

Framing Past Experience. The final experience I recount is the conclusion of Evan and Fiona's design process. The team's gripper had inflated and picked up a marker momentarily while experimenting, but popped when the team tried to demonstrate to the teacher. The resultant conversation illustrates the impact of framing on the decision for iteration.

Fiona:	Oh no. Arg…
Mr. Gray:	Ok, that's fine.
Evan:	So we can repair it though.
Fiona:	Yeah.
Mr. Gray:	But you were able to pick that up?
Evan:	Yeah.
Fiona:	Are you allowed to recommend to use what to do to make it better? Or do we have to do this all on our own?
Mr. Gray:	Just show your idea.
Evan:	But it worked. So it's fine. We're done.
Mr. Gray:	Right.
Evan:	Do you want to fix this or no?
Fiona:	So we are done? Does that mean that it's a success?
Evan:	Yeah.
Fiona:	We picked up… but you said a variety of objects. Does that really count?
Evan:	No, let me see… as long as it picks up something. Do you want to fix this and keep going, or no?
Fiona:	I don't know. So like how would we record our information if we only picked up one thing?
Mr. Gray:	OK, well step 12, then you say…
Evan:	It picked up the marker.
Mr. Gray:	The marker?
Evan:	We used a marker.
Mr. Gray:	Oh OK. Yes. So for step 12 you say um… we were able to pick a marker up but also describe how one of the fingers didn't bend as much. Like whatever…
Fiona:	Ok, so what design change would we make so we didn't do that? Like for the question where it says what would I change?
Mr. Gray:	It's not about design change. You were taking about how you could have more clips.
Fiona:	That'd be so fun. Oh cool. So now all we have to do is fill everything out.

As the team navigated the results of their design test, Fiona returned to some of the criteria established—the number and types of objects to pick up. Her perception of a discrepancy between the criteria and performance of their design led her to question whether or not they needed to keep working. On the other hand, Evan returned to the momentary success that the team had seen. The conversation smoothed some of the concerns Fiona had about documentation, given the circumstances of their design test, and the team ended their design.

The contexts of each team were different and the pathways to interpret and navigate failure and iteration were different. The expectations for iteration, by assignment from the teacher or as a natural part of the process, introduced a contrast in commitment to versions of design, and perhaps self-regulation in the process. At times, it ensured wholehearted commitment to the attempt, trying to make the most if it through planning and reflection. Yet, teams also reported a lack of commitment, looking forward only to the "final attempt" without learning along the way. The conversation and evidence I obtained surrounding these decisions is likely incomplete, and future investigation into designers' evaluations and adaptivity for subsequent iterations would be fruitful.

4.3.3.4 Reactions in Design

Reactions to design failure have been documented positively and negatively in past research (Lottero-Perdue & Parry, 2015). Understanding student reactions is important for scaffolding the educational environment and assistance in processing failure. In this case, I saw positive and negative reactions, for which I believe contextual factors play a role. As mentioned in the second theme of identifying failure, students were most often surprised by the failures they encountered in design. Some positive affect was noted when the designs were going well, accompanying evaluations like, "Oh look at that, that can grab some stuff." (Fiona). Negative reactions were more dramatic, especially when the causes were believed to be outside of the team's control. Sydney commented they had to "really focus on… trying not to give up after having to make so many grippers… because it was really frustrating and we got really discouraged." The intersection of failure and external causes was associated with this type of discouragement.

4.3.4 Synthesizing Self-Regulation Profiles and Design

The thematic analysis heretofore conducted uncovers nuance in the self-regulation patterns of beginning designers. Successes and failure play a role, but contextual and individual framing also impact performance evaluation. Furthermore, the recursive nature of self-regulation and design lead to the incorporation of prior information in new attempts, and can reinforce or remove barriers to meaningful iteration.

In pondering the use of self-regulation to navigate design, I am impressed again by the parallel nature of these processes. Here, I revisit the theoretical framework informing this work and propose further philosophical integration between design and self-regulatory thinking. The theoretical framework proposed to guide this work situated design and self-regulation processes in parallel, such that analysis, synthesis, and evaluation phases of design corresponded to forethought, performance, and self-reflection phases of self-regulation (Figure 9). Indeed, self-regulatory codes applied to the data correspond to steps in the design process. In hindsight however, especially in light of intermediate evaluations and flow of information throughout the design and regulation process, I perceive multiple cycles nested in the broader processes.

Each step in the design process is represented with corresponding self-regulation steps in Figure 31. The beginning of design incorporates forethought, performance, and evaluation to select an approach. The design process is instantiated with defining the problem, likened to goal setting in self-regulation. Brainstorming, to establish design variety, is likened to strategic planning, wherein the approaches for performance are determined. Research and constraints and criteria are used for refinement to the problem statement and ideas; in this way these are goal setting, as well as evaluation elements. A designer explores possibilities, predicting and evaluating the outcomes of brainstormed ideas. Selecting an approach entails a pivot in the design process by simultaneously evaluating and planning a solution. The proposal and prototype entail another microcosm of regulation; planning, performance, and reflection lead up to a refined design. Furthermore, each iteration is another regulatory cycle. Failure can occur throughout the design process, with examples summarized at intermediate and end points in the figure.

4.4 Summary

Using the methods in Chapter 3, this chapter reported findings from multiple information sources and analytical methods. First, I summarized the accounts of four design teams, portraying the chronology of their design attempts and testing outcomes. The purpose of these accounts was threefold: 1) to contextualize further analysis and the case context by offering a vicarious experience; 2) to demonstrate texture and variety in the design experiences of

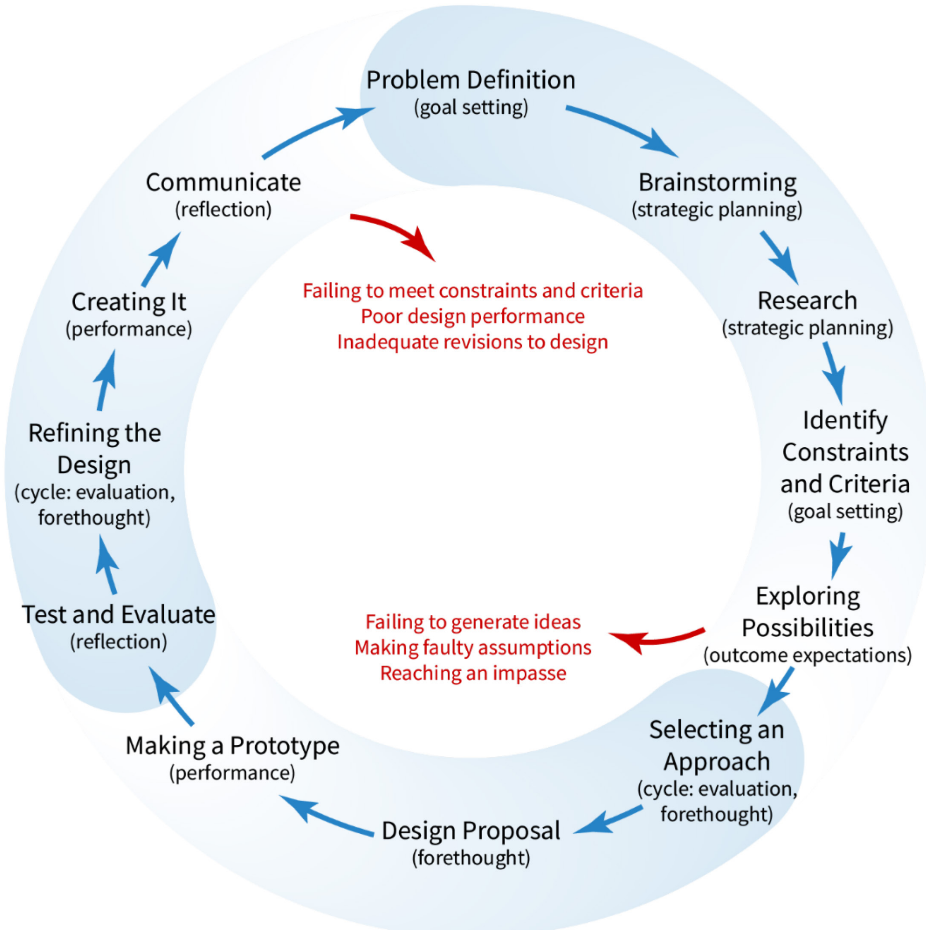


Figure 31. Revised integration of the design process and multiple self-regulation cycles. Shaded background color represents the microcosmic self-regulation cycles within the design process.

beginning designers; and 3) to bolster the selection of two teams for further analysis with linkography.

After a narrative account of the design experiences, linkographic analysis was conducted to describe patterns of forward and backward thinking in the design process of two focal teams—these patterns imitate the self-regulatory processes of forethought and reflection. Sydney and Jordyn demonstrated an interconnected design process that cycled between forward and backward thinking. Instances of design testing were well-connected throughout the design process. Evan and Fiona showed a more straightforward process, when considering the exchange between forward and backward thinking. The representation of these design processes asserted contextual impacts for design and self-regulation. Patterns from day-to-day structure, classroom requirements (e.g., documentation), and the design challenge organization of physical, iterative prototyping can be identified in the representations.

Finally, I conducted thematic analysis to focus on more specific self-regulation strategies employed by these designers, though holistically by incorporating all design teams again. I identified patterns of forethought, performance, and reflection, which align with the design process and inform one another reciprocally. In forethought, goal setting emerged from and oriented the design process; imagery associated with goals was also useful for building mental models of anticipated outcomes. Planning in the design process also supported improvements by embedding variety and taking lessons learned into future attempts. Psychological and motivational aspects of the design experience were mixed, with some positive framing and some negative framing. In performance, students used a variety of previously identified task strategies to navigate the design process. Design documentation, as a self-record of performance, was familiar and maintained, however students referred to externally generated records to inform design more often than their personal kept record. In reflection, small evaluations occurred throughout the design process. A seminal moment in each design process was the identification and attribution of failures. These reasons for failure also impacted decisions on whether and how to proceed in designing. Positive and negative reactions in design were briefly described. I concluded the thematic analysis by revisiting the theoretical framework guiding this work, and proposing further philosophical alignment between the design and self-regulation processes.

While exploring the soft robotics curriculum case context, I used several data sources and analytical methods to uncover and describe beginning designers' use of self-regulation. Self-regulation use, in consequence of design failures or successes, was of special interest to come to understand how beginning designers navigate these occurrences. From the findings reported in this chapter, I turn to the conclusions and implications reported in Chapter 5.

CHAPTER 5. CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

The purpose of this case study was to describe self-regulation use among high school designers as they encountered failure and iteration in the context of soft robot design. The case context, a developed soft robotics curriculum, presented a unique opportunity to examine elements of self-regulation, failure, and iteration, through repeated iteration cycles and the prevalence of failure in past use of the lessons. Two analytical methods—linkography and typological thematic analysis—have advanced the findings reported in Chapter 4. Enriched by triangulation from multiple information sources, these findings provide evidence of contextual influences on design and self-regulation processes. Thick description of design in practice also demonstrated the parallel nature of these two processes. However, even while there is alignment between the two processes, there was a unique trajectory by which each student carries out design and self-regulation.

To conclude this case study, I return to the initial guiding questions set out in Chapter 1 and point to insight obtained from the case design experiences. These research findings extend what is known about design cognition by the unique combination of design and self-regulation theories used in this research. Furthermore, the application of each analytical approach offers insight into the use of self-regulation by these beginning designers. Next, I translate these insights into implications for designers, educators, and researchers; limitations related to the methods and interpretation of insights; and future research possibilities.

5.1 Summary of Research Questions

The primary guiding question of this research was "How do beginning designers use self-regulation when navigating failure and iteration?" By answering two related questions in the study, I speak to the broader question of the use of self-regulation. Each question also presents an opportunity to synthesize findings across the analytical approaches used in this research.

5.1.1 Patterns of Self-Regulation

The first connected question was, "What are the patterns of self-regulation used by beginning designers when navigating failure and iteration?" The narrative chronologies speak to this generally, the linkographic results, specifically. This research affirms the contextualized, or situated, nature of both design and self-regulation. Complying with social cognitive theory, self-regulation is affected by personal, behavioral, and environmental factors (Bandura, 1986; Zimmerman, 2000). Environmental impacts are demonstrated by the class-instilled patterns. Perhaps chief among these is the day-to-day structure around the teachers' instructions (e.g., the frequent call backs to teacher instructions made by the teams; Figure 25). Connections from the beginning of class each day created a backbone to orient students with the day's objectives, provide contemporary content to reflect upon, and aid in time- and process-management. Teams' day-to-day evolution of ideas was also seen in the distribution of links among days (Table 8). With the exception of the first days, which were interconnected and to which most students referred back, links tended to be within the same day or to the most recent day.

Displays of the links among days also empirically support another pattern—the oscillation between forward and backward thinking, exhibited by varying degrees by the design teams (Figure 21). This structure aligns with the cyclical nature of divergence and convergence in design (Goldschmidt, 2016), or the co-development of the problem- and solution-spaces (Dorst & Cross, 2001). These directional shifts in thinking are also portrayed as teams analyzed the configuration and test results of their ideas, made attributions, and pivoted toward next iterations (Figure 26).

Themes in typological analysis also support this focus on directional thinking, including the collective relationship between strategic planning, evaluation and attribution, and future iterations. This research finding offers insight into how beginning designers might use information to shape successive phases of self-regulation. In the design process strategic planning was used to invest in design experimentation—looking forward. Similarly, it is through strategic planning that information from previous iterations in design performance was incorporated into the current attempt. After performance, reflection takes into account the outcome and attributions of failure—looking backward--before determining whether to iterate further—looking forward. When applied then, the design process may mitigate a form of dysfunction in self-regulation—ineffective forethought or planning—because forethought elements of goal setting naturally emerge from early phases in the design process (Zimmerman, 2000). Furthermore, it can support the development of an adaptive stance that attempts to improve on past performance.

By using linkography, I identify critical junctures in the design process observed. A pattern of these sticking points design self-regulation included the identification of design variables with which to experiment and the outcome of each design test. The development of brainstormed ideas built upon the interaction of these design variables, as a type of strategic planning (Figure 26). Furthermore, design testing moments were identified as centrally connected critical moves in the processes of both teams, successful or not. Extending the significance of testing, the soft finger testing of one team was critically connected in both directions. The bidirectional connections indicate that the finger test results built off of prior design work and contributed to next steps in the design process. However, despite these common patterns of experience, it is important to consider that personal factors overlaid the design process and made it different for each team.

Precise comparison of these patterns to past linkographic research is difficult to make because of the differing lengths of analysis. However, the limited structure of thinking seen in the linkographic representations, and lower link index than expert designers, verify these students as novice designers with opportunity to improve their ways of thinking in design (Goldschmidt, 2014).

5.1.2 Regulatory Strategies in Practice

The second connected question was, “What self-regulatory strategies do beginning designers employ in practice?” Thematic findings in the phases of self-regulation are most pertinent to address this question. Beginning design students used a variety of task strategies and structures to self-record the design process, during performance. Before and after execution in design, goal setting and evaluation were scaffolded by the design process. Students’ strategy use for forethought in the beginning of design is illustrated by the interconnected representations of their design process (Figure 24). Furthermore, themes of the second phase of analysis describe transitional points of self-regulation that propelled design and self-regulation processes forward.

During performance, the identified themes related to task strategies used, and covered an array of behaviors expected based on extant literature. The climate of design in these classrooms permitted help seeking from peers and the teacher. Students also used external resources (e.g., past design process examples and handouts). Research was embedded in the design process and useful for establishing mental models and goal visualization. Finally, the collaborative nature of the design process might be considered a task strategy; teams commented on the benefit of working in groups to "bounce more [ideas] off of each other" (Fiona). Students also worked together to check understanding and divide labor

Design journals were a central resource constructed during the design process that induced reflection (Figure 27). Students used drawing, charts, and descriptions to make sense of the design process. Figure 28 shows examples of these diagrams to orchestrate design variety. Figure 29 illustrates the process of documentation as one of record-keeping for performance monitoring. The documentation process is reflective in and of itself (Lin et al., 1999), yet students did not often reference their journals or reflect beyond the expectations of the design process. Even the timing of this example, at the end of the design process, limits the potential benefit that can be realized from documentation. This contrast between record-keeping and maintaining an interactive document can also be seen by in the frequencies of identified failures and plans for improvements. Designers commonly identified failure in design journals, but few were proactive to describe how future attempts could be improved.

These designers made changes in the course of their design; initial changes were design-focused, while later changes were process-focused. Students conducted evaluations throughout the design process, often informally based on forthcoming goals. More formal evaluations were associated with the performance tests of designs, and attributed to problems with materials, processes, or understanding (Table 10). Students perceived material problems to be external to themselves, therefore more frustrating. These attributions play an important role in motivation and affect, that this work only touched on (Schunk et al., 2014). Students' action in response to performance results coupled with additional themes describing transitional points of self-regulation. In forethought, strategic planning and outcome expectations were used to control (and improve) performance. In reflection, teams integrated their evaluations and attributions, to decide whether, and how, to iterate. These subprocesses in forethought and reflection were used by teams to transition information from iteration to iteration.

5.2 Implications

Taking into account the nuance afforded by this close investigation of design students, I have been concerned with exemplary knowledge, mentioned in Chapter 1. The findings are primarily descriptive, though by the rich detail, they portray tentative impacts of design and self-regulation in practice. It is at this intersection, of design and self-regulation, that the findings of this case study take place. My focus on the cognition of beginning designers offers insight beyond *what to do* when designing—the process—by uncovering *what to think* when designing. Therefore, this work has implications for design, design education, and researchers of design and self-regulation.

5.2.1 For Novice Designers

Behaviors shift in the course of completing a design task (R. S. Adams, Turns, & Atman, 2003; Goel & Pirolli, 1992). Various representations of design have encouraged cyclical or nonlinear processes (Crismond & Adams, 2012; Dubberly, 2004), yet praxis does not always illustrate these types of processes, especially for beginning designers. In the stories of these designers, there was a range of commitment to iteration—from frequent repetition to none at all. Thresholds for critical moves also showed a different number of divergent and convergent steps in the design process (Table 9). Furthermore, when I visually represented the time that these critical moves took place, teams showed different intensities of switching back and forth in modes of thinking (Figure 21).

From applying a framework of the self-regulation to the design process, I argue that these processes are compatible ways of thinking, which may support designers in iterative thinking. While this support may be most beneficial for beginning designers, to reinforce iteration, planning, and reflection, it can aid designers with a range of design expertise. The integration of design and self-regulation cycles

I communicate two similar descriptions of the problem-solving process. First, I use the terminology of design. Even with the co-evolution of problem- and solution-spaces (Dorst & Cross, 2001), initial design aims may be appropriately situated as sense-making process of problem definition. Propositions about the efficacy of design ideas are used to select an approach and proceed to explore the solution-space (Dong, Garbuio, & Lovallo, 2016). And new ideas must be evaluated and balanced for their impacts and efficacy (Salustri et al., 2009).

Next, applying the terminology of self-regulation, we see that the process might be oriented with goals in the design process, outcome expectations, and tentative performance. Performance monitoring and evaluation are used to make improvements. Task performance is also supported by a range of strategies, some selected in advance and others selected as needed.

Maintaining a record attains new importance for keeping track of what has been done, but also making accurate evaluations and informing future performance. Collectively, steps in the self-regulation of performance are a cyclical process of forward and backward thinking.

The intention of the process does not change, to develop a desirable solution to a problem. But, based on their compatibility, the philosophical integration of design and self-regulation processes might reinforce desirable patterns of design cognition and performance. An additional advantage of self-regulatory thinking may be to disentangle the association between performance success and learning. When used appropriately, strategic planning, self-experimentation, and adaptive stances in self-regulation offer reminders to engage deeper learning and process exploration. Failure can be met with acceptance, rather than aversion, in the design process. I anticipate changes in my own design work: to be more thoughtful in planning for design tests, accepting of design failure and iteration, and reflective to identify learning and performance improvements.

5.2.2 For Educators

A planned contribution of this research was the close analysis of a few design teams in each classroom. Description of the design processes and milestones, was afforded in greater detail than ordinary seen in teachers' requirements to support the development of many students. Therefore, in sharing how several students navigated the design process, this research offers design educators strategies to foster designerly ways of thinking and learning from success or failure in design.

As described in the implications for designers, fulfilling the design process with an emphasis on self-regulation can support a congruent process of decision-making and iteration. Teachers can support this development by modeling such behaviors, developing cognitive apprenticeships for students (Driscoll, 2005; Lin et al., 1999; Pellegrino & Hilton, 2012). In cognitive apprenticeships, teaching explains patterns of thinking and can support the parallel development of design and self-regulation. Both teachers in this study attempted to influence goal orientations and adaptive stances in their communication with students. Furthermore, the use of authentic teaching strategies (e.g., anchored instruction) stands out as a strategy for supporting reflection and iteration. In authentic learning activities, situational talk-back offers a realistic feedback on thinking, and contextual factors may naturally evoke reflection and planning strategies (Jackson & Strimel, 2018; Schön, 1983; Strimel, 2014). For the design challenge herein, design failure was evident and led to reflection as designers interpreted and navigated their next steps. Self-regulation and design are contextualized, and teaching structures are brought to bear on these processes. Therefore, realism in our teaching structures can engender useful patterns in design and self-regulation. Design documentation can also be reframed as a cognitive device, rather than merely a record-keeping device, to encourage a reflective and transformative design process (see Figure 30). In class learning activities there is typically a degree of limited autonomy because the activities are teacher-generated. Nonetheless, these strategies can work to move students from reactive to proactive modes of regulation, where forethought and performance control are used to manage outcomes.

Toward learning from design outcomes, I also advocate meaningful timing for assessment and intervention. In classes, many assessment strategies have also been identified to foster self-regulation:

- Requiring documentation of student processes (Lin et al., 1999); this is effectively the self-recording element of the performance phase.
- Using formative assessment or portfolios where students can explain what they have done and reflect further on their work (Binkley et al., 2012).
- Giving feedback on process, not only products of student performance (Pellegrino & Hilton, 2012).
- Involving students in assessment (Glyn Thomas, Martin, & Pleasants, 2011).
- Or using metacognitive prompts or reflective questions (Aurah et al., 2014; Peters-Burton, 2018).

Application of these assessment strategies is known to support the routine development of self-regulation, reflective design, and learning while designing. Reflection in design necessarily comes after design attempts, however, if students encounter failure, it can turn to a learning opportunity or discouragement.

When should assessment be conducted? As indicated by the list just offered, and affirmed in this research, assessment should be conducted throughout design. Students make evaluations in the midst of design. Still, formative assessment, especially when it involves students, can draw out further evaluations and reflection to shape performance. These touchstones present an opportunity to get students to step back, conduct further planning and orientation, and evaluate what has been done so far. Early assessment can also act as a stimulus to identify failure while there is still time to overcome it (Sleezer et al., 2016). I believe it unfortunate that design is often concluded with hypothetical improvements—"What would you do differently next time?"—instead of enabling those chances to refine and improve the products of design. I admit that there is not always time, but the successive iterations seen in this case context ultimately fostered learning and success, even when it did not occur at first.

A related question arises, when should intervention occur in design teaching? Based on the experiences analyzed, I offer pointed recommendations. While failure can serve as a learning experience, what is important is how it is framed. A positive climate is necessary, that encourages students to keep trying and try as many approaches as possible (Kapur, 2008), reiterates that it is okay to fail (Lottero-Perdue & Parry, 2017a), and maintains a level of trust between student and teacher (Trenshaw et al., 2014). The timing of intervention should consider motivational aspects of the team (or student) and efficacy of their work. As students move away from positive affect, or when their behavior is relegated to trial-and-error or brute force approaches instead of reflective practice, I consider intervention appropriate. The purpose of an intervention might be to defuse discouragement, or support evaluation, strategic planning, or performance. If a team is satisfied with mediocrity (e.g., when Evan and Fiona negotiate that their design was satisfactory; Figure 27), a different type of intervention may be necessary to challenge further iteration: work to raise goals, foster interest or task value, identify fallacies in evaluation, and even sow dissatisfaction to grow toward further iteration attempts. In short, intervention should take place when teachers perceive a chance to encourage mastery goal orientations or adaptively (Dweck, 2006).

5.2.3 For Design Researchers

The use of think-aloud protocols to approximate cognition is familiar in both self-regulation research and design research. Compared to past examples of self-regulation research, this research was situated in a novel context of design, which facilitated observation of regulatory strategies. And compared to past design research, this work was unique in that it conducted think-aloud research in the course of normal classroom work. Furthermore, to my knowledge, linkographic analysis has only been applied for K-12 research in one other study (Blom et al., 2018). I adapted the linkographic approach by special attention to moments of failure and success. Finally, this study presented a unique combination of linkographic and thematic analysis to uncover further insight into cognitive patterns. The unique combination these features represents a test case for researchers, to examine what worked well and what did not. Based on my experiences in this research, I offer insight, which is extended into the limitations section next.

The dual application of analytic methods was driven by the guiding questions of this study and my pragmatic approach to undertake it. I believe the resemblance of linkographic diagrams to forethought and reflection in self-regulation affords special insight into regulatory thinking. Nonetheless, the flexibility of linkographic methods (e.g., Goldschmidt, 2014; Hatcher et al., 2018; van der Lugt, 2000) may be of interest for researchers of other cognitive processes. Initially, my research design conceived a deeper integration between the analytic approaches, however this did not come to fruition and they stand as complementary approaches. Together, however, each analytic approach seems to offer a different perspective on the guiding question, which I found useful.

While the multi-day application of design analysis conducted in this case study was unique, the preponderance of data raised challenges concerning analysis. This issue was particularly true of the linkographic analysis which is grounded in fine-grained design moves by default (Goldschmidt, 2014). As a result, the identification of design moves and links was labor intensive (Goldschmidt & Tatsa, 2005). I addressed this challenge by choosing focal teams for the linkographic analysis. Capacity to navigate and make sense of so many design moves remained an issue. R. S. Adams et al. (2017) described some of the challenges of "big data" in design analysis, including time-consuming data analysis procedures and difficulty in identifying resultant patterns. These researchers proposed visualizations as one tool for interpreting the results, which dovetails with the linkographic diagrams, and to which I also turned to understand ancillary aspects of the linkographic analysis (e.g., Figure 20 and Figure 21). Indeed, I present novel visualizations for the interpretation of linkography evidence. In Chapter 4, my disaggregation of links among days (Table 8) and representation of critical move density over time (Figure 21) are new in this work. I also managed the number of critical moves by my focus on selected moves in the design process—occurrences of success or failure.

5.3 Limitations

This case study research was intentionally qualitative, with a small sample to afford close investigation and rich detail in analysis. The study evidence was limited to the experiences of these eight designers and, within their experiences, to salient aspects that I felt characterized their journey in design. Despite Sydney and Jordyn's persistence to try again in their design, I was uninformed and could not include their culminating attempt. However, their process is still exemplary for its pattern of iteration and the information obtained by linkographic analysis. I acknowledge that other perspectives may exist and be underrepresented in the account. My proximity to the designers may have had an impact on the experience, their vocalizations or behavior. Or, students' thinking may be incompletely captured in the research. However, in the duration of the experience I observed students "settle in" to the research procedures (e.g., wearing a microphone) and I believe their actions to be authentic. Furthermore, the reliability methods of triangulation by multiple information sources and a member check after the lessons had concluded, provided mechanisms to assure accuracy.

In dealing with the large scale of data to ingest for linkography, I chose to narrow my focus to two design teams, and parsed evidence visually. An alternative approach would be to use more granular analysis of design dialog, which may yield different results. Analysis of lengthy data in the design process is susceptible to the same memory effects of participants—that is, not making connections backward because of memory limitations. Future work could encapsulate episodes of the design process for linkographic analysis; in a more concentrated episode it is possible that analysis could be more refined, even by multiple reviewers. Despite alternative approaches, to investigate the intersection of self-regulation and design, the methods here are sensible and can give confidence to future researchers of these domains.

5.4 Future Research

The detail and perspectives offered within this account of beginning designers, holds many opportunities for further investigation. I propose several opportunities to extend this work in two directions, with the current analytical methods as a footing.

First, the network of interconnected moves captured in the linkographic analysis can be investigated for further structure. In such a large number of moves, feasible research would likely focus on singular aspects of the representation. For example, analysis of critical moves could seek to understand complex patterns for what makes a design move "stick." I identified design variables and testing moments within this grouping, but other clusters of moves likely exist and could help design educators insert more sticking points in design. Other research might focus on differences in the structure of the link span, understanding the purpose of short or longer link spans. While this work overlaid instances of testing on the linkographic representation, and found a connection between these experiences and critical moves, future analysis could narrow down to examine the ripple effects of design testing on the interconnected process. Are there different *quantitative* patterns immediately after failure or success? And other design process phases might be overlaid to examine the interconnected nature of design. Buildup to design decision making, such as when teams brainstorm ideas and select an approach, were beyond the scope of this research but, if overlaid in linkography, may manifest flow in the design process more formally.

I have presented the linkographs broadly, only unpacking a few episodes from design that align with the structure. To balance the labor-intensive nature of this work with a desire for greater reliability and description of patterns, interrater reliability might be conducted on small episodes of the linkograph. Follow-up verification of these sequences in the design process could be complemented by further thick description of the account.

Related to thematic analysis, themes identified in this work demonstrate transient thinking through design and self-regulation. Important elements in forethought and self-reflection turn the process back on itself to make cycles of improved performance. However, the decision to iterate is influenced by environmental and personal factors. Future research could also explore decision-making for iteration, including the roles of causal attribution and self-satisfaction in triggering iteration.

Traversing the design process along with beginning designers has offered insight into patterns of design thinking and self-regulation, especially when navigating failure and success. These students will design again, whether in a course of study or part of everyday problem solving. It is my hope that students can proficiently navigate the times when their designs do not work, using past experiences of failure and scaffolding to reflect and plan ahead, turning their design failures into a valuable learning experience.

APPENDIX A. SOFT ROBOTIC GRIPPER DESIGN BRIEF

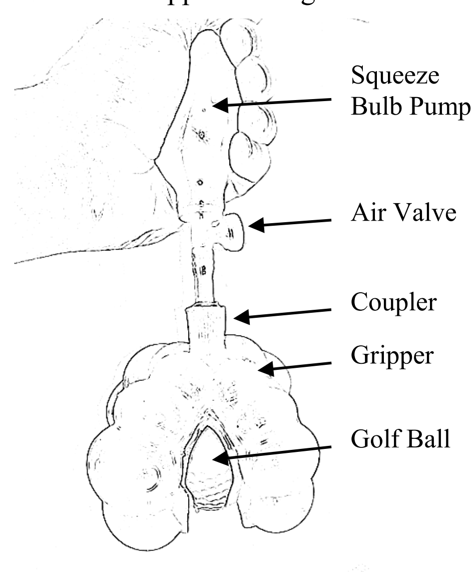
Background Scientists, engineers, and designers know the importance of documenting their work. Ideas, thoughts, experiments, and sketches all have a place in their notebooks. Other names for these notebooks are: Inventor's Logbooks, Science Notebook, Engineer's Notebook, and others. Thomas Edison documented the details of his ideas and inventions in over 3,500 notebooks.

Design Problem Worldwide there are more people eating and fewer people producing food; we need to be more efficient and not damage what we have. You have been hired to design a robotic gripper to help a small farm operation be more efficient in picking up fragile produce. They have several different crops but their main yield is tomatoes about the size of a golf ball. Your gripper needs to help a farm worker accurately pick up the crop and sort it, all without damaging the food. Gripper should pick up, hold and release the tomatoes (golf balls). You should also be prepared to give training on your gripper and explain your design decisions (why you made it the way you did). Document your work using your electronic Engineering Design Journal.

Specifications

1. The robot gripper must be able to pick up a golf ball by inflating with the squeeze bulb pump.
2. The gripper must be able to securely hold the golf ball for 5 seconds.
3. The gripper must be able to release the golf ball by opening the air valve.

Gripper Testing



Materials

- Soft Robot Gripper Mold
- Ecoflex 2-part silicone
- Squeeze Bulb

Deliverables

1. Students working in groups of two will develop a solution to the soft robotic gripper design brief.
2. The process used to develop the solution should be recorded using the students' electronic engineering journals. The journals should include sketches, pictures, and video of the solution.
3. Students will present their solution and electronic engineering design journal to the class.

APPENDIX B. EBSCO EDUCATION SOURCE SEARCH QUERY

The following search terms were used to conduct the systematized literature review in Chapter 2:

#	Query
S1	"productive failure" OR "failure" OR "impasse" OR DE "Failure (Psychology)"
S2	DE "Science education" OR DE "Science education (Elementary)" OR DE "Science education (Middle school)" OR DE "Science education (Secondary)" OR DE "Science education (Higher)" OR DE "Computer science education" OR DE "Science classrooms & equipment") OR DE "Technology education" OR DE "Technology education (Middle school)" OR DE "Technology education (Secondary)" OR DE "Technology education (Higher)" OR DE "Engineering education" OR DE "Engineering education in elementary schools" OR DE "Engineering education in universities & colleges" OR DE "Mathematics education" OR DE "Mathematics education (Elementary)" OR DE "Mathematics education (Middle school)" OR DE "Mathematics education (Secondary)" OR DE "Mathematics education (Higher)" OR DE "Design education" OR DE "Design education in elementary schools" OR DE "Design education in secondary schools" OR DE "Design education in universities & colleges" OR DE "Engineering design education" OR DE "Engineering design education in elementary schools" OR DE "Engineering design education in secondary schools" OR DE "Engineering design education in universities & colleges" OR DE "STEM education" OR DE "STEAM education" OR DE "Problem Solving"
S3	"learning" OR "instruction" OR "education"
S4	S1 AND S2 AND S3 Limiters – Publication Type: Academic Journal, Conference Paper, Conference Proceeding; Language English

APPENDIX C. LITERATURE ON FAILURE CHARACTERIZED BY GRADE, DISCIPLINE, AND RESEARCH DESIGN

Table 11. *Selected Failure Article Characteristics in K-16 STEM or Design Education.*

Article	Grade Level	Discipline	Sample	Research Design[a]
Akatugba and Wallace (2009)	High	S	6	QUAL
Berglund et al. (2009)	Undergrad	E	16[b]	QUAL
Hutchison-Green et al. (2008)	Undergrad	E	12	QUAL
Kapur (2008)	High	S	309	QUAN / qual
Kapur (2010)	Middle	M	75	QUAN + qual
Kapur (2011)	Middle	M	109	QUAN
Kapur (2012)	High	M	133	QUAN
Kapur (2014a)	Middle	M	136	QUAN
Kapur (2014b)	High	M	186	QUAN
Kapur and Bielaczyc (2012)	Middle	M	302	QUAN / qual
Kapur and Kinzer (2009)	High	S	177	QUAN
Loibl and Rummel (2014)	High	M	279	QUAN
Lottero-Perdue and Parry (2015)	Elementary	E	108[b], 14[b]	QUAL + quan
Lottero-Perdue and Parry (2017a)	Elementary	E	74[b], 10[b]	QUAL + quan
Lottero-Perdue and Parry (2017b)	Elementary	E	254[b], 38[b]	QUAL + quan
Matlen and Klahr (2013)	Elementary	S	52[c]	QUAN
Pan et al. (2010)	Undergrad	T	65, 45	QUAN → qual
Pantziara and Philippou (2015)	Elementary	M	321	QUAN
Pathak et al. (2011)	High	S	4	QUAL
Plenty and Heubeck (2013)	Middle	M	519[c]	QUAN
Sleezer et al. (2016)	Undergrad	E	21	QUAL
Trenshaw et al. (2014)	Undergrad	E	37, 8	QUAL
Trueman (2014)	Undergrad	S	26	QUAN
Upadyaya et al. (2012)	Elementary	M	69	QUAN
Westermann and Rummel (2012)	Undergrad	M	59[c]	QUAN / qual

[a] research design using mixed method notation (Creswell, 2009); capitalization represents the emphasized phase of research, + denotes simultaneous data collection, / denotes embedded phases for explanation, and → denotes sequential data collection
[b] teacher participants reflecting on student behavior
[c] final sample size due to attrition

APPENDIX D. EXPOSITION ON CONTEXT DEVELOPMENT

As described in the Case Context and Context Development and Positionality sections, my past experience with the soft robot design context was impactful on my interest in the case and interpretations of case evidence. This section elaborates my involvement in the project, with overlap to what was reported previously.

As a graduate research assistant, I was invited in the "Soft Robotics to Broaden the STEM Pipeline" project three years ago, during negotiations with National Science Foundation program officer, and have been involved since. The project was conceptualized to increase STEM participation, especially among girls, by changing student paradigms for robot design. The project means, whereby interest might increase, were to bring soft robot design principles and experiences to 9th grade technology and engineering classrooms, testing the feasibility of robot fabrication in a classroom context. The design-based lesson plan presented a challenge for students to make a soft robot gripper to assist in an agricultural food harvest and sorting operation. Soft robotics is an emerging approach to robotics which uses flexible components (e.g., rubber and fabric) instead of rigid materials. Such designs embed safety for human interaction (Majidi, 2013; Trimmer et al., 2013) and offer potential for new applications (Trimmer, 2013). The proposed gripper fabrication process has largely stayed the same: mix a two-part silicone rubber to cast the top half of the robot in a mold, then adhere a less elastic layer to 1) create an enclosed air chamber and 2) constrain the robot motion to curve. Yet, the instructional experience and design materials for students needed to be developed.

Once the project was awarded, work commenced to develop the fabrication processes and lesson plans; I contributed to both aims by modeling and prototyping fabrication materials on the one hand, and outlining and drafting lesson materials on the other. The design for fabrication settled on the use of a modular, 3D printed mold, which was intended to support student design variation on several gripper characteristics: primarily the length and clip arrangement (Zhang et al., 2017). The design also supported segmentation of the gripper to make only one finger. Using several finger variations, students investigated principles of soft robot design before making a complete gripper—their final design. In this way, design prototyping and iteration were prefigured into the instructional experience.

The lesson sequence intended for students to learn about underlying scientific principles of pneumatics and pressure, then conduct research and taken an initial attempt at making a soft robot finger. Following the first version of their finger design, variation among class designs and teacher-led discussion would draw attention to the need for greater exploration of design alternatives to inform the final, completed gripper design. Following several rounds of iteration and testing of soft robot fingers, students would produce a completed gripper. The lesson culminated with student demonstration of their gripper and a presentation on their design process.

First Implementation of the Soft Robot Lesson Plan

Following the first year of development, including several pilot lessons which I delivered, teaching materials were presented to teachers in a hands-on professional development meeting. The meeting instantiated their partnership in the research project. Teachers experienced soft robot design personally, realizing that it was more difficult than it seemed: though all of the teachers were ultimately successful, their success was not neat. I use the word neat in allusion to messiness of this robot fabrication process in action. Due to improper mixing or spills, the two-part silicone rubber would not cure (harden) and the liquid rubber would contaminate work surfaces and gloves. Nonetheless, teachers were excited about the project and prepared to implement it at various times throughout the year.

Based on class scheduling, there were three main implementation times for the soft robot lessons. After each, we heard feedback from the teachers describing the challenges and successes in the lessons. However, my recall of this feedback immediately turns to hearing about the mess and low success rate among classes. Additional containers were sent to teachers to aid in pouring the two-part silicone. Yet it was in the discovery of a chemical conflict, that the research team (myself included) gained the greatest hope for supporting student success. We experimented and learned that the nitrile gloves supplied to the teachers would inhibit the curing process of the silicone rubber, leading to both the mess and failed designs. New gloves were used for the third lesson implementation.

Following the third implementation, I visited classes with another graduate student to observe the success of student robot designs in person. Through our testing of 54 final grippers, only 29 (54%) were able to successfully complete the design challenge of holding a golf-ball for five seconds (Zhang et al., 2017). In addition, we saw multiple modes of failure: clogged air chambers or an insufficient seal, uneven curvature, or even air leaks from bubbles. Through our discussion and analysis, we could infer changes in the fabrication process or robot design which would lead to success: using the right amount of silicone to adhere the bottom layer; working and curing the robot on an even surface; and mixing slowly then allowing time for air bubbles to escape before curing the robot. Yet, with only nascent exposure to soft robots, I do not think I could have immediately diagnosed these failures or reflected on the changes needed to overcome them; my own learning illustrates the importance of reflection to have informed iteration in the soft robotics context. Are 9th grade students able to arrive at these conclusions? Do they have windows of reflection in their design to arrive at these conclusions? Are these design failures a function of a low-tolerance fabrication process, a limited number of iterations (i.e., given more time would there be more success), or lack of understanding regarding soft robot design?

As one of the instructional designers for this experience, I also found myself asking whether the level of success was good, or good enough. To what degree should students be scaffolded to success in design? What structure exists in this design experience to support student design success? And what do students make of their own success or failure while seeing the circumstances of their peers? Students' explanations of events (attributions) are shaped by the environmental context of learning, therefore, the overall level of success should be an instructional consideration.

The empirical success rate offers one metric by which to gauge the experience, yet further information was needed to describe the experiences and processes of student designers in this context. Other empirical evidence from this first year of implementation indicated that student perceptions were volatile, with about 34% of students changing their attitudes of engineering self-efficacy, motivation, or interest (Jackson et al., 2018). On average, the soft robot lesson performed as well as a traditional robotics lesson in changing these engineering perceptions. Taken together, the results of the first year indicated moderate success, yet a need to improve the experience and investigate it further.

Refinement to the Lesson Plan

In the continued development of the soft robot design experience, one change recommended and led by teachers was to change the lesson context. For continuing teacher participants, the lessons were moved to a medical technology context (from the agricultural harvest and sorting context); the design brief and lesson engagement activity were both changed to accommodate the new setting, though the cyclical structure remained.

A second change was to reframe the design and testing of soft robot fingers as research instead of prototyping. From a review of the design journals of participating students, the developmental trajectory of their final gripper design seemed disjointed—when ideas did not work, new ideas were attempted on a whim, rather than stemming from failure analysis. By positioning the finger design and tests as research, we hoped that the context would suggest the learning that could take place from these tests, mitigate negative effects of failure, and end up informing final gripper design in a more coherent way.

We also attempted to move away from some of the process scaffolds which had been in place in the first year. For example, we had provided teachers with a step-by-step paper and video guide to the fabrication of grippers, complete with a troubleshooting section to guide the identification and correction of common errors. While this was originally intended as a guide for teachers, or students needing educational accommodations or who might have missed the beginning demonstrations in class, we saw it used as a teaching tool. The guide was based on the design of a single successful gripper with clear imagery, therefore we assumed it would constrain the design creativity of students.

As teachers modified the lessons, my own sense of ownership for the lessons diminished; these ideas were largely removed from my involvement. The fulfillment of these changes varied from teacher to teacher to produce the case setting of this study. For the teachers I observed, the year-to-year lesson development and their previous history teaching the lessons played a role in shaping the soft robot design experience for the beginning designers in their classes.

Researcher Bias

My own involvement in the development of the design experience played a role in my interpretation and observations, and interest in studying this context and research direction. Yet, while I was intrinsically motivated to study this context, I maintain that it offers a lens whereby self-regulation and strategies for navigating failure can be observed. In order to uncover beginning designers' use of self-regulation strategies, I valued their own words in response to the context and design challenge. Certain aspects of the lessons were important: the nature of this design experience, with embedded iteration and evident failure, made it important for study; that it is part of a larger investigation is not as important for this case study.

Based on my past involvement, I entered observations of the case with several assumptions. I assumed this would be a challenging experience for beginning designers. First, the materials are new for students. Second, the fabrication process is sensitive to detail. Subsequently, I assumed that some of the designs produced by students would not work or would not work as well as expected. My past experience in the development of this project was beneficial here, as I was able to perceive potential problems in the fabrication process that may have been overlooked by beginning designers. The anticipation of potential failures drew my attention to the design situation and reactions of the team as they later encountered failure. Third, linked to inoperable designs, I also assumed students would have a chance to make several versions of the soft robot artifacts and vary their designs. In this process I hoped that students would uncover the fabrication and design details to change in order to produce a successful design. Said another way, I expected the first designs would not work as well as the students hoped and that dialog would articulate the desired improvements. These self-reflections would come to frame the next attempts, including criteria for success in the design.

APPENDIX E. INTRODUCTORY SCRIPT FOR OBSERVATIONS AND AUDIO RECORDING OF DESIGN

The following script, based on procedures recommended by van Someren et al. (1994), was used to introduce participating student teams to the purpose of the research and think-aloud process:

> You agreed to participate in research about the robotics lesson you are having. I am interested in how you go about the design process so that we can improve how it is taught in the future. You don't need to work on the design any differently than you normally would—keep working in your design journal and working together like normal. I don't want to interrupt your work. I am just asking you to work together and try to say everything that goes through your mind while you are designing—in all design steps.
>
> So that I can remember how you design, I'd like to audio record you each day while you work by having you wear a microphone:
>
> > This is the recorder and microphone *(show equipment)*.
> > You turn the recorder on by sliding this switch *(show Hold switch)*.
> > Then, begin recording by pressing the record button *(show Record button)*.
> > You can tell it is working by this light *(show LED indicator)*.
> > Please begin each day by saying your name and the date so I can tell who is designing.
>
> Each day when you get to class you should get a recorder from me or your teacher, begin using it, and say your name. After these lessons I will write up what you say under a pseudonym and delete the recordings so that someone won't be able to tell it is you.
>
> I will also take pictures of your work (not you) occasionally so that I can see how the design is coming along. I'd like to end each day by taking a picture of your design journal since it will change from day to day. Do you have any questions about what to do?

Throughout the observations, participants may be heard giving evaluation or interpretation of their thinking. Statements such as the following were used to remind them to speak what they are thinking only:

> Please be sure to just say what you are thinking. You don't need to explain why.

Participants also needed reminders to think out loud, such as the following:

> Please keep on talking.
> What are you thinking about?

APPENDIX F. SEMI-STRUCTURED INTERVIEW QUESTIONS

The following interview questions provided a beginning to the interview protocol with design teams. Teams were interviewed by class, meaning two teams (four students) were able to respond together.

Focus group questions (copied from the broader research study):

- Generally, tell me about your experience with robotics in this course.
- Describe the approach you took to the robotics challenge and the processes you used.
- What are the challenges of the robotics lessons?

Interview questions:

- Member check my story of their design artifacts
  (Share my outline of the design process and images of the design artifacts with the summary of inflation results. Do you agree?)
- When you started designing, what did you do?
- What were you thinking about as you worked on your soft robots?
- How did you decide your gripper design? What did you do differently between stages of your design? Why?
- Would you say your design was successful or not? What do you think led to your success or failure of your design?
- What did you do when your design failed (didn't work)?

Additional questions were asked to one team that had continued building without being observed:

- Can you tell me about the last two grippers you made? What happened when you designed and tested them?

APPENDIX G. INFORMAL CODEBOOK

Linkography

Design Move: A step, act, or operation to transform design situations (Goldschmidt, 2014, p. 42)

Design moves can "vary in length and duration" (Goldschmidt, 2014, p. 42). A move should be identified when idea, specifications, questions, knowledge, or comments are shared (Hatcher et al., 2018). New ideas or elaboration on an idea each constitute a move. The identification of a move is interpretive; summarize the statements or context.

Examples:

Transcript	Design Move
How many uh… joints do you think we should? Like, I have 3 joints	• Asks about number of joints to include, refers to own hand having 3
Ok, so here, so far I have our two ideas. I have the one with five and it's equal. And I have one with and it's bigger, smaller. Do we have any other world changing ideas?	• Introduces one idea to have 5 evenly spaced clips • Introduces another idea to have bigger and smaller clips • Asks if there are more ideas
Ok, let's open it. Let's go. Let's go get it.	• Fingers are removed from the oven after the first curing
S: I'm going to start off the next mold with a brand new bag full of materials. That way, hopefully they won't be as sticky. J: Or be easier to work with. S: Yeah, they'll be easier to work with.	• Decide to also use new materials for the mold so it isn't as sticky • Agree, may be easier to work with × (not identified - ongoing consensus)

Design Links: A common sense connection between two design moves

Design links are identified by comparing each pair of moves and asking if there is a link. Rules for links include changes on an idea, of inspiration from an idea. Repeated words are not necessarily linked. Dialogical elements can be used to determine links: agreement, questioning, consensus. Links are formed to the earliest related move, unless new information is in common between moves (i.e., if Move 4 and Move 8 are linked, and Move 4 and Move 12 are linked, Move 12 will not automatically be linked to Move 8).

Examples (not inclusive of all links for these moves):

Move		Linked Move	
(361)	Clarifies that there are two different packets to use	(310) (318)	Gives handout of measurement guide and step sheet Gives tutorial packet that has step-by-step information
(525)	Tells to stop mixing because it has been long enough	(518)	Reminder about mixture length
(941)	Gets gloves to use for mixing	(940)	Begins pouring one part of silicone mixture
(67)	Decides to focus on joint placement to control bend location and grip	(15) (22)	Idea to have design flexibility in clip spacing Hypothesis about bending at joint placement
(450)	Elaboration that silicone may be less sticky after curing overnight due to “natural heating”	(448)	Comment on curing overnight being different than in an oven because it might be less sticky

Self-Regulation (Typological Analysis)

Goal Setting: Deciding specific desired outcomes of performance

Mark goal setting for statements regarding desired outcomes, e.g., constraints and criteria. However, based on the approach, outcomes may vary: for example, if students choose to test a few ideas deliberately, they may state goals of the test such as exploring variables. Do not mark goal setting for approach decisions (“Let’s test several fingers,” strategic planning) or predicted outcomes (“I think it will work,” outcome expectations).

Examples:

“Ours was focused on a hand, like an actual human hand.”

“So do we do it now or do we wait a minute?” … “No, we have to cut it.”

“We have to build a hand. We have to be able to pick up objects for... five seconds.”

“Yeah, we’re making the mold and then we have to pump air into it. And it’s supposed to bend.”

“I wish it would just be like, ‘This is your goal. This is your limitations...’”

“Just trying to remake our mold again.”

Strategic Planning: Selecting strategies to accomplish the task

Mark strategic planning when students are choosing how to approach the problem. When adjusting the frame of reference. This may lead to modified goals. Mark when students plan design variety. Do not mark when modifying performance in action (self-experimentation).

Examples:

"I'm writing a chart out for select an approach. For when I'm ready to start that part of it."

"Like, do we want to be practical or do we want to be creative?"

"So the brainstorming itself is about the clips, like the spaces in between?"

"For our fingers we started to try multiple ideas to see which one would probably work the best out of all of them."

"Do you want to do it the same way?" … "Do the same way."

Self-Efficacy: Statements about personal beliefs of ability

Mark self-efficacy when students refer to confidence or abilities to perform the task. Do not mark self-efficacy when comments are on interest (intrinsic value). Self-efficacy is also distinct from outcome expectations which are beliefs about the end results of performance, not being able to do it. For example, believing in ability to get an A grade is different than believing the outcomes that will produce such as a job. And belief that a therapy program will be beneficial is different than belief in ability to abide by it.

Examples:

"We sealed it like four times and it always popped without fail. There was no way to fix it."

"Like, in theory this is easy but I think that once you actually do it it's going to be like trying to get a claw machine to grab something. And it's just going to fall out."

"OK I'm going to trust you to pour the coupler because obviously I'm not that successful at it."

Outcome Expectations: Belief statements about the end results of performance

Mark outcome expectations when referring to the end results of performance. Outcome expectations link the course of action to results. Do not mark outcome expectations if pertaining to confidence in performance ability (self-efficacy) or discussing the efficacy of various performance approaches (this should be marked as strategic planning).

Examples:

"Well, we watched the video and I saw 'Oh, the finger inflated.' But I didn't really understand what our process was going to be to make the finger."

"Ok, I think this one will work."

"How well do you think this one's going to work?"

Intrinsic Interest/Value: Motivation or value for the task, whether or not there are rewards

Mark intrinsic interest for motivational aspects of performance. This may include highlighting the value of the task, novelty of the task, or benefit to learning.

Examples:

"It was a lot different than something we had done before. It was a different material. It was sort of a little different concept."

"This is so fun. Ours looks pretty solid if you wanted to know."

"I'm excited to mix up this silicone stuff."

"I mean he probably cares. I think our grade cares."

Goal Orientation: Motive for performance, from mastery of the concept to performance for others

Goal orientation refers to whether the task is done for learning and improvement, or for performance to show others. Mark goal orientation for statements about the reasons for completing the task.

Examples:

"I think that ultimately learning how to complete the project, without the end result being a complete and total failure, is what you should consider successful."

"This isn't a race. It isn't, 'Let's see who can get three fingers done first.' That's not the point of this."

"Aren't we actually testing these though? Like as the grade?" … "Has any of our testing affected your grade?"

Self-Instruction: Self-description on how to perform the task

Self-instruction was obfuscated due to the think-aloud nature of the research. This code should not be used.

Imagery: Forming mental pictures or visualization for task performance

Due to the mental nature of imagery, this code was not used.

Attention Focusing: Ability for learner to filter out distractions and focus on task performance

Control over the environment and avoiding distractions are evidence of attention focusing. Due to the analytical process of removing off-topic conversation, the data does not represent a clear picture of students' attention focusing strategies. This code should not be used.

Task Strategies: Specific strategies used to aid in performance

Code for the use of specific strategies. Examples in Zimmerman (2000) and Azevedo and Cromley (2004) include note taking, information searching, summarization, inferences, hypothesizing, help seeking, or time management. When something is deliberately done to aid in the task it should be coded.

Examples:

"When I researched it I was able to see step-by-step what we were doing."

"But I don't know how much we need. Should I ask someone that already did it?"

"Maybe when I'm going to get it out, you go get the stuff."

"Let's look at the instruction book thing. Can you take this? What does it say?"

Self-Recording: Capturing performance progress

Mark for documenting progress or contextual factors of performance. Especially, documentation of performance such as design journaling, should be noted.

Examples:

"This big packet is basically a summary of the video. You must refer to this."

"Hold on, I'm drawing this picture."

"I'm writing that there was no build up in it. Like no air pressure because of the holes it released."

"And I think that spacing, maybe we should have a little bit less... here let me draw the cross thing so you can tell what I'm talking about."

Self-Experimentation: Varying aspect of performance or self-testing for performance improvement

Mark self-experimentation for when the learner is searching for patterns of performance. For example, trying a new approach to inflate the robots or experimenting with performance approaches. Do not mark for experimentation or manipulation of design variables (strategic planning).

Examples:

"Hang on. We just need to stretch this out. Here, can you put your hand over this so that it can't expand?"

"Hold on, I'm trying something."

"Try picking something up. Try picking this up."

"Maybe if we scoot it down, it wouldn't pull up so much. It's kind of worth a try, I guess."

Self-Evaluation: Comparing performance against established standards or goals; denoting an event as a success or failure

Mark self-evaluation for comparison against goals, past performance, or normative (social) factors. Mark whether or not the deliberation is clear; therefore, statements about idea efficacy are included. Simply put, whenever students stated that a test was successful or a failure (e.g., not good) it should be marked. Mark evaluative decisions, not necessarily deliberations (causal attributions).

Examples:
"Get a little bit more over there."
"We definitely made some errors here because some of the clips came up."
"Only the ends of a couple of fingers are blowing up."
"Is this enough research? I think it's not enough."
"Like this finger's the best but we're going to use all of them anyways."

Causal Attribution: Developing an explanation for performance outcomes

Mark for elaborations of self-evaluation results, or deliberations leading up to the evaluation (that contain causes). Attributions are multifaceted. They may be internal or external, stable or unstable, and controllable or uncontrollable.

Examples:
"So in hindsight it probably would have worked really well. But we just didn't test it properly."
"That's why it's not going pressure throughout because there's an air bubble."
"So the hole's somewhere. I don't know where."
"It's definitely because this is thinner. Like you see..." … "It just must've been... something must've knocked it."

Self-Satisfaction/Affect: Affective states as a result of performance evaluations

Mark for satisfaction, dissatisfaction, or other affective states connected to performance evaluations. Codes include positive and negative attitudes.

Examples:
"Something that we really focused on was trying not to give up after having to make so many grippers. Because it was really frustrating and we got really discouraged."
"This is really satisfying. Look we made that."
"Oh, no... All of my work."
"Although, I'm really impressed that we kept the seal and did that the first time. So that's good."

Adaptive-Defensive:	Whether the learner is open to change or defensive about approaches and learning taken

Mark for statements related to flexibility or fixing ideas. Examples include changing approaches or strategies, or references to trying something new this time, compared to a past time. (In this way they may seem to be in performance stages of regulation.) Defensive stances include self-handicapping or avoidance that are taken to prevent further dissatisfaction.

Examples:
"I think we focused more on the changing of how we were executing the process rather than actually changing our design."
"If they work, great. Report that. If they didn't work, that's fine. What was the issue?"
"So now we're trying to make it so the fourth finger works too."
"And once you've done that, you're then going to design, construct, and evaluate a hand. And then hope that it meets the criteria and constraints. If it doesn't, what are you going to do? Anyone? [girl: Test it.] [boy: Cry in the corner.] Cry in the corner. Correct. [laughter] And then after you're done crying, you will redesign, right?"

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VITA

Andrew Jackson
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EDUCATION

Ph.D., Engineering and Technology Teacher Education 2018
Instructional Design Graduate Certificate
Ross Fellowship Recipient
Purdue University, West Lafayette, Indiana

Dissertation: A Case Study of High-School Student Self-Regulation Responses to Design Failure
Advisor: Nathan Mentzer, PhD

M.S., Engineering and Technology Teacher Education 2015
Purdue University, West Lafayette, Indiana

Thesis: Instructional Design Considerations Promoting Engineering Design Self-Efficacy
Advisor: Nathan Mentzer, PhD

B.S., Technology and Engineering Education, *magna cum laude* 2013
Brigham Young University, Provo, Utah

SCHOLARSHIP *(Entries are sorted reverse chronological order by authors and title.)*

JOURNAL ARTICLES

Jackson, A., Godwin, A., Bartholomew, S.R., & Mentzer, N. (2018). *Learning from failure: A systematized review*. Manuscript submitted for publication.

Jackson, A., Mentzer, N., & Kramer-Bottiglio, R. (2018). *Soft robotics as emerging technologies*. Manuscript submitted for publication.

Jackson, A., Mentzer, N., & Kramer-Bottiglio, R. (2018). Pilot analysis of the impacts of soft robotics design on high-school student engineering perceptions. *International Journal of Technology and Design Education*, Advanced online publication. doi: 10.1007/s10798-018-9478-8

Jackson, A., & Strimel, G.J. (2018). Toward a matrix of situated design cognition. *CTETE Research Monograph Series, 1*. doi: 10.21061/ctete-rms.v1.c.3

Bartholomew, S.R., Strimel, G.J., & Jackson, A. (2018). A comparison of traditional and adaptive comparative judgment assessment techniques for freshmen engineering design projects. *International Journal of Engineering Education, 34*(1), 20-33.

Zhang, J., Jackson, A., Mentzer, N., & Kramer, R. (2017). A modular, reconfigurable mold for a K-12 soft robotic gripper design activity. *Frontiers in Robotics and AI, 4*, 1-8. doi: 10.3389/frobt.2017.00046

CONFERENCE PROCEEDINGS

Jackson, A., Mentzer, N., & Kramer-Bottiglio, R. (2018, June). *Intersecting self-efficacy and interest: Exploring the impact of soft robot design experiences on engineering perceptions.* Paper presented at the 2018 ASEE Annual Conference & Exposition, Salt Lake City, UT. Retrieved from https://peer.asee.org/30712

Jackson, A., & Mentzer, N. (2018, April). *Making meaning of design failure.* Paper presented at the Council on Technology and Engineering Teacher Education/International Technology and Engineering Educators Association 2018 Annual Conference, Atlanta, GA.

Jackson, A. (2018, March). *Validity evidence for the general engineering self-efficacy and engineering skills self-efficacy scales with secondary students.* Paper presented at the 2018 ASEE Illinois-Indiana Section Conference, West Lafayette, IN. Retrieved from http://docs.lib.purdue.edu

Jackson, A., & Mentzer, N. (2017, June). *Cluster analysis in engineering education.* Paper presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/28044

Jackson, A., Mentzer, N., Zhang, J., & Kramer, R. (2017, June). *Enhancing student motivation and efficacy through soft robot design.* Paper presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/28280

Jackson, A., Mentzer, N., Kramer, R., & Zhang, J. (2017, June). *Maker: Taking soft robotics from the laboratory to the classroom.* Paper presented at the Make It! Event during the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/27741

Jackson, A., Zhang, J., Kramer, R., & Mentzer, N. (2017, June). *Design-based research and soft robotics to broaden the STEM pipeline (work in progress).* Paper presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/27963

Strimel, G.J., Bartholomew, S.R., Jackson, A., Grubbs, M., & Bates, D.G.M. (2017, June). *Evaluating freshman engineering design projects using adaptive comparative judgment.* Paper presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/28301

Jackson, A., Mentzer, N., Laux, D., Sears, D., & Asunda, P. (2016, June). *Student self-perceptions of design and creative thinking.* Paper presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, LA. doi:10.18260/p.25927

Laux, D., Jackson, A., & Mentzer, N. (2016, June). *Impact of collaborative learning on student persistence in first year design course.* Paper presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, LA. doi:10.18260/p.25536

Chesley, A., Mentzer, N., Jackson, A., Laux, D., & Renner, M. (2016, June). *Integrating technology, English, and communication courses for first-year technology students.* Paper presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, LA. doi:10.18260/p.25414

Knapp, S., Jackson, A., & Renner, M. (2016, April). *Gender differences in design motivation*. Paper presented at the 2016 ASEE Illinois-Indiana Section Conference, Moline, IL. Abstract retrieved from http://www.wiu.edu/cbt/qc/engineering/asee/ASEEIllinoisBookletWebVersion.pdf

Jackson, A., Mentzer, N., & Zissimopoulos, A. N. (2015, June). *Factors of group design decision making.* Paper presented at the 2015 ASEE Annual Conference & Exposition, Seattle, WA. doi:10.18260/p.24098

Mentzer, N., Jackson, A., Richards, K. A., Zissimopoulos, A. N., & Laux, D. (2015, June). *Student perceptions on the impact of formative peer team member effectiveness evaluation in an introductory design course.* Paper presented at the 2015 ASEE Annual Conference & Exposition, Seattle, WA. doi:10.18260/p.24759

Jackson, A., & Mentzer, N. (2015, March). *Teacher self-efficacy: A qualitative study of the effects of practice on graduate student instructor beliefs.* Paper presented at the Society for Information Technology & Teacher Education International Conference 2015, Las Vegas, NV. Retrieved from https://www.learntechlib.org/p/150115/

Jackson, J., Jackson, A., & Shumway, S. (2015, March). *High school sound recording curriculum utilizing the iPad.* Paper presented at the Society for Information Technology & Teacher Education International Conference 2015, Las Vegas, NV. Retrieved from https://www.learntechlib.org/p/150391/

Connolly, P., Mentzer, N., Laux, D., & Jackson, A. (2014, March). *Development and implementation of courses to meet the requirements of a core curriculum.* Paper presented at the ASEE Illinois-Indiana Section Conference & RosEvaluation Conference 2014, Terre Haute, IN. Retrieved from http://ilin.asee.org/

Connolly, P., Mentzer, N., Laux, D., & Jackson, A. (2014, March). *Establishing a core curriculum at the college level.* Paper presented at the ASEE Illinois-Indiana Section Conference & RosEvaluation Conference 2014, Terre Haute, IN. Retrieved from http://ilin.asee.org/

Jackson, A., & Wright, G. (2013, March). *Cyberbullying prevention curriculum in technology classrooms.* Paper presented at the Society for Information Technology & Teacher Education International Conference 2013, New Orleans, LA. Retrieved from https://www.learntechlib.org/p/48585/

REVIEWED CONFERENCE PRESENTATIONS

Jackson, A., & Mentzer, N. (2018, April). *Soft robotics in the classroom*. Presentation at the International Technology and Engineering Educators Association 2018 Annual Conference, Atlanta, GA.

Mentzer, N., Jackson, A., Kramer, R., & Zhang, J. (2018, April). *Pilot results: Increasing STEM self-efficacy and motivation through soft robotics design*. Poster presented at the International Technology and Engineering Educators Association STEM Showcase, Atlanta, GA.

Mentzer, N., & Jackson, A. (2018, April). *Soft robotics to broaden the STEM pipeline*. Presentation at the Council on Technology and Engineering Teacher Education/International Technology and Engineering Educators Association 2018 Annual Conference, Atlanta, GA.

Jackson, A., Mentzer, N., Kramer, R., & Zhang, J. (2017, March). *Increasing STEM self-efficacy and motivation through soft robotics design.* Poster presented at the International Technology and Engineering Educators Association STEM Showcase, Dallas, TX.

Jackson, A., Mentzer, N., Kramer, R., & Zhang, J. (2017, January). *Increasing STEM self-efficacy and motivation through soft robotics design.* Presentation at the 2nd Annual Indiana STEM Education Conference, West Lafayette, IN.

Jackson, A., Mentzer, N., Kramer, R., & Zhang, J. (2016, June). *Increasing STEM self-efficacy and motivation through soft robotics design*. Presentation at the 13th Annual ASEE Workshop on K-12 Engineering Education, New Orleans, LA.

Jackson, A., & Mentzer, N. (2016, March). *Evaluating and enhancing group design decision making*. Presentation at the International Technology and Engineering Educators Association 2016 Annual Conference, Washington, DC.

Jackson, A. (2016, March). *Graduate student forum: Increasing STEM self-efficacy and motivation through soft robotics design*. Presentation at the Council on Technology and Engineering Teacher Education/International Technology and Engineering Educators Association 2016 Annual Conference, Washington, DC.

INVITED PRESENTATIONS

Jackson, A., & Mentzer, N. (2015, April). *COT integrated freshmen experience—evolution, theory, practice and research*. Presentation in the Technology Leadership and Innovation Colloquia, West Lafayette, IN.

OTHER SUBMITTED PUBLICATIONS

Jackson, A., & Wright, G. (2013). Incorporating cyberbullying prevention curriculum in technology classrooms. *Journal of Undergraduate Research, 18*. Retrieved from http://jur.byu.edu/?p=549

TEACHING EXPERIENCE

UNIVERSITY TEACHING

IT 50700 – Applied Data Analysis (Co-Instructor) Summer 2018
Purdue Center for Professional Studies (ProSTAR)

Provided interactive demonstrations in statistical techniques for a distance education course. Created weekly statistical programming tutorials in the R programming environment.

TECH 12000 – Design Thinking in Technology Fall 2013 – Fall 2015
Purdue Polytechnic at Purdue University

Instructor of record for flipped learning environment focused on design and innovative thinking. Responsible for weekly instruction, grading, and office hours for up to 3 sections per semester, with approximately 30 students each. Contributed to weekly mentorship meeting with other instructors. Conducted empirical research to examine learning and motivational impacts of course material.

Engineering Projects in Community Service (Co-Instructor) Spring 2015 – Fall 2015
College of Engineering, Purdue University

Conducted weekly design status reports for up to 4 interdisciplinary design teams in a service-learning course. Provided educational technology consultation. Modeled relationship building with local project partners through onsite visits and user experience research. Evaluated design documentation and presentations at mid- and end-of-semester milestones.

TEE 125 – Communication Technologies and Systems (Teaching Assistant) Fall 2011
School of Technology, Brigham Young University

Teaching assistant for introductory technology education course. Led class instruction on introductory web design and graphic design software.

K12 TEACHING

Summer Residential Teacher (7^{th} – 12^{th} Grade) 2015 – 2016
International summer camp, Gifted Education Resource Institute, Purdue University

Developed and delivered problem-solving and creativity courses. Provided learning accommodations for about 30 accelerated learners and English language learners.

Super Saturday Teacher (5^{th} – 8^{th} Grade; Co-Instructor) 2015
6-week Saturday program, Gifted Education Resource Institute, Purdue University
Encouraged creative thinking and problem solving through Rube Goldberg machine design in informal learning setting.

Career and Technology Education Teacher (7^{th} – 8^{th} Grade) 2012 – 2013
Albion Middle School, Canyons School District, Utah
Designed and delivered required, introductory technology instruction for 7^{th} grade students. Integrated standards of 7 technology domains to develop open-ended design challenges.

PROFESSIONAL TRAINING

Trainer, IT Training, Brigham Young University 2011 – 2012
Provided technical training for BYU students and employees. Maintained high aptitude for learning and teaching using over 20 software programs. Organized and assisted professional development goals for 18 trainers. Created new employee handbook and assisted in hiring.

OUTREACH ACTIVITIES

2018 Soft robotics professional development for teachers, Tucker, GA
2017 Soft robotics professional development for teachers, West Lafayette, IN
2016 Hosted visiting high school students with soft robotics fabrication experiences
2015 Innovation to Reality (I2R) Workshop on soft robotics fabrication

HONORS AND AWARDS

2018 Donald Maley Outstanding Graduate Student Citation, International Technology and Engineering Educators Association
2017 21^{st} Century Leadership Academy Fellow, International Technology and Engineering Educators Association
2015 Ross Graduate Fellowship, Purdue University for recruitment of outstanding Ph.D.-track students
2013 “Project based learning through multimedia projects,” Canyons Education Foundation Grant for technology based school improvement
2012 “Incorporating cyberbullying prevention curriculum in technology classrooms,” Office of Research and Creative Activities Grant for undergraduate mentored research
2012 1^{st} Place Teaching Lesson Contest, Technology Educators Collegiate Association
2011 1^{st} Place Video Communications Contest, Technology Educators Collegiate Association
2011 Top 10 Finalist for International Video Contest, The Church of Jesus Christ of Latter-day Saints

TECHNICAL SKILLS

Adobe Creative Suite
HTML and CSS
Photography and Videography
Qualtrics Research Suite
R Statistical Software
Digital and Manual Fabrication (3D Printing, Laser Cutting, Woodworking)

MEMBERSHIP AND ACADEMIC SERVICE

2015 – Present	Member, American Society for Engineering Education
2011 – Present	Member, International Technology and Engineering Education Association
2015 – Present	Reviewer, American Society for Engineering Education Annual Conference
2016, 2018	Judge, Technology and Engineering Education Collegiate Association Competitions
2017	Reviewer, Advances in Engineering Education
2015, 2017	Moderator, American Society for Engineering Education Annual Conference
2011 – 2012	President, Brigham Young University Technology Educators’ Collegiate Association
2011 – 2012	Adobe User Group Manager, Provo, UT