Investigating How K-12 Students Engage in Engineering Practices

By

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Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Learning, Teaching, and Diversity

August, 2014

Nashville, Tennessee

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To my family for their support and encouragement

ACKNOWLEDGEMENTS

This research was supported, in part, with funding from the National Science Foundation. I am thankful for the guidance of my advisor, Dr. Richard Lehrer. He led me to an interesting research topic, helped me clarify my ideas and methods, and gave me regular feedback on my thinking and my writing. He was generous with his time and unwaveringly supportive of me both professionally and personally. In short, he was an excellent mentor. In addition to my advisor, I would also like to thank the remaining members of my committee, Dr. Leona Schauble, Dr. Barbara Stengel, and Dr. Donald Compton. You have been my allies in this process by contributing your time, insight, support, and humor. I could not have made it to this point without each of you helping me at various places along the way. Thank you also to my fellow graduate students, and in particular, the members—past and present—of the Lehrer/Schauble research team, for helping improve my work. Finally, thank you to my wife, Amy. You were my sounding board and my editor throughout this process. Everything I wrote, you helped me make better. Every time I reached an impasse, you helped me overcome it. When I lacked motivation, you supplied it. When I was down, you lifted my spirits. You truly are an amazing partner.

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CHAPTER I

INTRODUCTION

The National Research Council (NRC) recently advocated incorporating pre-college engineering practices into K-12 science standards to support its vision of an integrated STEM (i.e., science, technology, engineering, and mathematics) education (Katehi, Pearson, & Feder, 2009; NRC, 2010, 2012). This vision was reaffirmed in the Next Generation Science Standards (2013), which emphasize engaging K-12 students in shared science and engineering practices to enable them to learn crosscutting concepts and core ideas in science (Achieve Inc., 2013).

Engineering design, the iterative process by which engineers solve problems, is increasingly becoming viewed as a means for supporting these forms of learning. For example, participating in engineering design helps students learn about core concepts in science such as complex systems, structural stability, and heat transfer (Hmelo, Holton, & Kolodner, 2000; Roth, 1996; Schnittka & Bell, 2011). However, the impact of participating in specific engineering practices (e.g., troubleshooting, reverse engineering, and considering trade-offs) on student learning has been comparatively neglected. Accordingly, in this three-paper dissertation I investigate how students build conceptual knowledge by participating in engineering practices. Moreover, because learning is intertwined with self-expression and personal interest, I also investigate the array of resources students bring to engineering design and examine how students draw on these resources to help them achieve functional and aesthetic design goals.

In the first paper, I reviewed K-12 design-based science literature to explore how contemporary design-based science learning environments engaged students in science and engineering practices. A chief goal was to ascertain how the field has approached the design of integrated learning environments to promote students learning science content. Results showed that design-based science learning environments engaged students in seven prominent activities: (a) solving ill-structured problems, (b) evaluating models, (c) discussing ideas and artifacts, (d) redesigning based on failure, (e) accessing materials, (f) negotiating constraints, and (g) keeping records. Although these activities supported a range of science and engineering practices (e.g., asking questions, engaging in argument from evidence, iterative refinement, and optimization), they did not support a subset of engineering practices, such as considering trade-offs, reverse engineering, or mathematizing, the progressive description and redescription of a system in mathematical terms (Kline, 1980; Lynch, 1988). These results indicated the importance of developing integrated learning environments to foster engineering practices that are not currently supported in design-based science learning environments.

Papers two and three are empirical papers based on a study in which 28 seventh graders authored and built their own paper pop-up books during 15 days of instruction, an activity also know as paper engineering. Paper engineering instruction was based on a curriculum originally developed by Benenson and Neujahr (2009). Together, Rich Lehrer and I modified the original paper-engineering curriculum to provide opportunities for students to produce visually appealing pop-ups by drawing on: (a) instances from their personal lives, (b) knowledge of Internet memes, and (d) other outside interests. Additionally, we drew parallels to related instruction in language arts by anchoring the curriculum's tasks and activities to the production of a five-page pop-up book. For example, students planned out aspects of their story, such as the introduction, climax, main characters, and setting by writing and illustrating page and story maps that served as templates for their pop-up book designs. Furthermore, we developed opportunities for students to engage in engineering design by posing design challenges (i.e., activities in which students designed and built pop-ups that performed in particular ways or had specific attributes) derived from previous iterations of instruction. Solving design challenges promoted student participating in approximations of engineering practice, such as reverse engineering and troubleshooting.

In the second paper, I asked three questions: (a) What design resources do students bring to paper engineering? (b) How does engaging in the practices of reverse engineering and troubleshooting help students make sense of pop-up mechanisms? and (c) How do students draw on design resources and knowledge of pop-up mechanisms to realize their design goals when building pop-up books. To characterize the resources students brought to the design of pop-up books, I analyzed three sources of data: (a) pre-instruction surveys in which students reported what they knew and valued about pop-up books, (b) pre-instruction interviews in which students examined and explained what they noticed about five paired comparisons of commercial pop-ups illustrating different types of paper folds, and (c) page and story maps in which students planned the story and individual pages of their books. I found that many students valued aesthetic aspects that set pop-ups apart from each other, such as a diversity of colors and objects and differences in the size and complexity of folds. In addition, I found that students noticed attributes of pop-up books such as directional motion and the degree to which a pop-up extended out of the book. Finally, I found that students agreed that an interesting story was an important attribute of a good pop-up book and that many students planned their books around themes that included events stemming from other books (50%) and from their own lives (29%).

To examine relations between practices and knowledge, I analyzed small-group and whole-group discussions from across instruction in which students described how they solved different design challenges. I found that engagement in the practices of reverse engineering and troubleshooting promoted students reasoning about the systems they designed, but also that students developed heuristics to solve the problems they encountered when building pop-ups.

Finally, I examined students' accounts of how they met their design goals by analyzing post-instruction interviews in which students displayed the pop-ups they built and described the decisions they made when building them. I found that students' design goals and constructions were influenced by their pre-existing design resources and by their participation in the practices of reverse engineering and troubleshooting. In particular, students reported using specific folds in the service of telling their stories and using knowledge of pop-up structures to solve aesthetic problems they encountered when building their pop-ups.

In the third paper, I focused on investigating pop-up design as a medium for self-expression and as a forum for developing design aesthetics. In addition, I also continued to probe how students understood relations between pop-up structure and function and how participating in the practice of troubleshooting contributed to students developing these understandings. To accomplish these goals, I conducted several new analyses, drawing on additional data sources I did not use in paper two, and extended one of the analyses I performed in paper two.

I asked three questions in the third paper: (a) What is the nature of the pop-ups students build and what does this indicate about pop-up design as a medium for self-expression? (b) What do students understand about pop-up structure and function? and (c) How does participating in the practice of troubleshooting contribute to students learning about pop-up structure and function? To better understand the opportunities for self-expression in paper engineering, I first cataloged all of the pages in the 28 books students designed and built. I then classified each page according to the following dimensions: (a) types of folds present, (b) number of pop-ups on the page, (c) connectivity of the pop-ups on the page, (d) paper strip composition, and (e) method of illustration. I found that authoring pop-up books was a vibrant forum for self-expression, as students constructed pages with different types of folds, customized the paper strips they used to build pop-ups, and illustrated their pop-ups in various ways. In addition to cataloging and classifying the pages students built, to illustrate the affordances of paper engineering for students with different academic profiles, I also conducted a comparative case study based on students' post-instruction interview responses and on supplemental data provided by the teacher about their academic histories. I found that although the teacher had different expectations for the two students going into the project, both of them meaningfully engaged with the material while demonstrating different interests. For example, one of the students used knowledge of the folds she learned about to purposefully design for pop-up motion, while the other student focused almost entirely on authoring a captivating story and paid less attention to the folds he used.

To discover what students understood about pop-up structure and function, I developed a coding scheme and coded portions of individual student interviews from three separate points across instruction. Elements of the coding scheme included describing: (a) how to attach pop-ups to the page so that they worked correctly, (b) how to make tall and short pop-ups, (c) how to attach pop-ups into the book so that they would not protrude out of the book when closed, (d) how to make symmetric and asymmetric pop-ups, (e) the direction of pop-up motion, and (f) the magnitude of pop-up motion. I found that building particular types of folds promoted students noticing basic attributes of pop-up function (i.e., that pop-ups need to span the middle of the book and attach to both sides of the book) and that building other types of folds promoted students noticing how pop-ups moved with different magnitudes of motion.

Finally, to understand how participating in the practice of troubleshooting contributed to students learning about pop-up structure and function, I analyzed classroom discussions in which students described the problems they encountered when building pop-ups and explained how they used troubleshooting to solve those problems. This analysis was similar to one of the analyses I performed in paper two, with two notable exceptions. First, I narrowed the analysis by drawing only from whole-group activity. Second, I yoked this question to my second research question by highlighting instances of troubleshooting in which students demonstrated learning about the elements of pop-up structure and function present in my coding scheme. I found that organizing paper-engineering instruction around solving design challenges promoted student participation in the practice of troubleshooting. Furthermore, as students resolved design challenges, they developed practical knowledge of pop-up structure-function relationships, such as how pop-ups: (a) attached to the page, (b) moved in one direction or another, (c) popped up very tall or very short, and (d) popped up symmetrical or asymmetrical. This practical knowledge was often expressed as heuristics and not as formal calculations or canonical explanations of structure-function, corroborating the findings in my second paper.

As a whole, these three papers form the kernel of a research program focused on investigating K-12 students' competency with engineering practices. In the first paper, I explored the presence and absence of engineering practices in contexts in which students engaged in the design of physical artifacts to learn science concepts. In the second paper, I investigated the pre-existing resources students brought to the design of pop-up books and how engaging in the practices of reverse engineering and troubleshooting influenced how students made sense of pop-up mechanisms. In the third paper, I examined pop-up design as a medium for self-expression as well as how troubleshooting contributed to the nature of student understandings about pop-up structure and function. In addition, throughout the papers, I maintained a focus on developing learning environments that emphasized students participating in engineering practices. Taken together, these papers provide a foundation for further work investigating how students participate in engineering practices to learn core ideas that span science and engineering.

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CHAPTER II

DEVELOPING INTEGRATED LEARNING ENVIRONMENTS TO PROMOTE SCIENCE AND ENGINEERING PRACTICES

Recently, there have been appeals to integrate pre-college engineering content into K-12 science standards at points where disciplinary learning goals overlap. For example, in 2010, the National Research Council (NRC) recommended integrating engineering content into the current science standards through mapping, “drawing attention explicitly to how and ‘where’ core ideas from one discipline relate to the content of existing standards in another discipline” (p. 28), and through infusion, “including the learning goals of one discipline in educational standards for another discipline” (p. 23). Similarly, in 2012, the NRC outlined a framework for integrating engineering content into the Next Generation Science Standards (NGSS) emphasizing shared practices (e.g., developing models and engaging in argument), crosscutting concepts (e.g., systems, patterns, and change), and common core ideas (e.g., engineering design and the link between engineering and society). These initial attempts at integration highlight the mounting importance of developing *integrated learning environments*—settings where students have opportunities to participate in science practices such as asking questions, engaging in argument from evidence, and carrying out investigations—while also engaging in engineering practices such as troubleshooting, reverse engineering, and considering trade-offs.

In this review, I explore how design-based science learning environments engage students in science and engineering practices with an eye towards discovering how to develop integrated learning environments so that they promote students learning science content. Using

Lehrer's (2009) *design elements* of a learning ecology framework as an analytic tool, I review the design-based science literature to answer three questions:

- What types of activities do students engage in when participating in design-based science learning environments?
- How do these activities relate to students participating in science practices and learning science content?
- How do these activities align with established engineering practices?

In the next section, I provide a brief overview to introduce readers to the National Research Council's rationale for integrating engineering content into K-12 science standards. I follow by outlining Lehrer's (2009) design elements framework and by explaining how I employed it to answer my research questions.

Integrating Engineering Content into K-12 Science Standards

Broadly speaking, the push to integrate engineering content into science standards is part of a larger movement to integrate science, technology, engineering, and mathematics (STEM) content in a phenomenon known as integrated STEM (iSTEM) education. Early notions of iSTEM education were anchored in documents such as *Science for All Americans* (Rutherford & Ahlgren, 1989), the *Benchmarks for Science Literacy: Project 2061* (AAAS, 1993), the *National Science Education Standards* (NRC, 1996), and the *Standards for Technology Literacy: Content for the Study of Technology* (ITEA, 2000). Each of these publications acknowledged the integrated nature of STEM education and contributed, to some degree, to initial conceptions of iSTEM education. Although iSTEM education includes technology and mathematics, I focus here on the intersection of science and engineering because this form of integration is at the forefront of iSTEM education (Achieve Inc., 2013; Katehi, Pearson, & Feder, 2009).

The impetus to integrate engineering into K-12 science standards is based, in part, on changing views of science and engineering education. In the past, educators treated science and engineering as separate disciplines composed of distinct content and practices. Teaching science and engineering in this way propagated the notion that these two disciplines are discrete. This viewpoint began to change as educators and researchers recognized points of convergence between how scientists and engineers build disciplinary knowledge (Lewis, 2006; NRC, 2012). For example, Lewis (2006) argued that engineering design and scientific inquiry were conceptual parallels because they shared "uncertainty as a starting reasoning condition" (p. 271) and because they both relied heavily on "analogical reasoning" (p. 271). In addition to changing views of science and engineering education, science education is also currently undergoing a shift from a content and process-oriented approach towards a practice-oriented approach (NRC, 2012). The shift towards a practice-oriented approach in science education has led to an increased recognition of interdisciplinary practices. For example, in science, modeling often involves designing devices, which has traditionally been positioned as an engineering pursuit.

Recent efforts to integrate science and engineering content have come on the heels of several influential publications examining the state of K-12 engineering education in the United States. First, in 2009, the NRC released *Engineering in K-12 Education: Understanding the Status and Improving the Prospects.* In this report, the NRC explained that STEM education did not, but should, emphasize the interconnectedness of the STEM disciplines (Katehi et al., 2009).

Next, in 2010, the NRC published a second report, *Standards for K-12 Engineering Education?* In this report, the NRC recommended *not* developing standards for K-12 engineering education, but rather integrating engineering content into the current science standards through mapping and infusion. Mapping and infusion were meant to solve several issues the NRC identified with establishing independent standards for K-12 engineering education. These issues included the underdeveloped engineering teacher-training pipeline (i.e., the lack of infrastructure necessary to train and certify engineering teachers) and the undue burden that adding another content area subject to the curriculum would have on schools and teachers (NRC, 2010).

Finally, in 2012, the NRC published *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. In this report, the NRC outlined its current perspective: engaging in science and engineering practices helps students better understand the nature of the work of scientists and engineers. Additionally, the NRC explained that focusing on practices helps reduce the tendency for students to learn science as a monolithic set of facts and procedures (NRC, 2012). This Framework served as the basis for the Next Generation Science Standards, introduced in 2013.

To summarize, over the past few years, there has been a sustained push to integrate science and engineering content in the move toward iSTEM education. This push has resulted in a perspective that emphasizes engaging students in science and engineering practices. In this paper, I take the position that integrated learning environments should support students learning about core disciplinary ideas by engaging them in science and engineering practices.

Conceptual Framework

Throughout this paper, I use the term *practice* frequently. I consider a practice to be a recurrent form of activity, recognized and employed in a discipline to generate and revise knowledge. Hence, disciplinary practices are inherently epistemic (Knorr Cetina, 1999). Moreover, I contend that engaging students in practices, or in approximations of practices, may provide them with opportunities to (a) experience first-hand how scientists and engineers establish, develop, and refine knowledge and (b) build knowledge about science and engineering in ways that parallel how practicing scientists and engineers build knowledge.

Developing learning environments demands consideration of how to organize materials and coordinate activity within a system. As a guide, I turned to Lehrer's (2009) description of critical elements to consider when crafting learning environments to help students develop disciplinary practices. In his paper, Lehrer outlined five elements to consider when developing learning environments to promote disciplinary practices: (a) tasks (i.e., What do students do? What are the affordances and constraints of these forms of activity?); (b) material means (i.e., What technologies, broadly described, are available for students to work with?); (c) inscriptions (i.e., What do students write and record?); (d) modes and means of argument (i.e., How do students make and contest claims?); and (e) activity structures (i.e., What recurring activities do students participate in?). Collectively, these five elements are known as design elements[1]. In Lehrer's framework, the learning ecology (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) emerges from interactions among the design elements. For example, asking students to find a solution to a problem often requires them to adopt modes and means of argument that support making claims. In turn, activity structures that highlight generating and defending claims may lead students to produce inscriptions as evidence. Disciplinary dispositions emerge as teachers and researchers orchestrate these design elements in classrooms (Lehrer, 2009).

I also take the perspective that design is an essential activity of all integrated learning environments. The term *design* is used in several fields (e.g., engineering, architecture, and art), and has various meanings in each. For instance, design can refer to creative processes, sets of

[1] Lehrer does not actually identify activity structures as an element in this framework, however, he has recommended considering activity structures as a fifth element when developing learning environments, as illustrated in Lehrer, Strom, & Confrey (2002).

drawings or plans, different types of artwork, or to any number of items manufactured at the end of a process. Here I take design to be the complete social process, composed of a collection of solitary and collaborative activities distributed across space and time, leading to a common goal—the construction of a tangible and useful object or device (Bucciarelli, 1988). Throughout the paper, I refer to these objects and devices as *artifacts*.

Design plays an important role in professional engineering, K-12 engineering education, and K-12 science education. Design is also the central activity of professional engineering (Bucciarelli, 1994; Dym, Agogino, Eris, Frey, & Leifer, 2005; Simon, 1996). In addition, design-based activities are typically found at the core of most K-12 engineering curricula (Brophy, Klein, Portsmore, & Rogers, 2008; Katehi et al., 2009). Furthermore, K-12 science educators are increasingly using design-based activities to teach scientific concepts such as complex systems (Hmelo, Holton, & Kolodner, 2000), electromagnetism (Sadler, Coyle, & Schwartz, 2000), and heat transfer (Schnittka & Bell, 2011). Hence, examining the tasks, material means, inscriptions, modes and means of argument, and activity structures in contemporary design-based science learning environments may suggest arrangements that support students learning science and engineering practices and content. It should be noted that I consider design-based science learning environments as precursors to integrated learning environments because they represent contexts in which students can potentially engage in both science and engineering practices.

Method

Selection Criteria

To locate design-based science studies for this review, I performed database searches using different keyword combinations, read abstracts and papers from those searches, mined the references from those papers to identify additional studies, and asked advice from professionals in the field. Because this review is meant to be representative rather than exhaustive, I have included only empirical studies published in peer-reviewed journals and book chapters.

Since the term *design-based science* is quite general, I chose to narrow its definition along three dimensions. First, I considered the nature of the designed artifact. To reduce the number of studies in the review to a manageable number, I included only studies where students designed hard artifacts (e.g., model elbows, alarm systems, and lightweight bridge trusses) rather than soft artifacts (e.g., computer simulations and molecular animations).

Second, I considered the type of learning under investigation. Because I am interested in developing integrated learning environments that promote science learning, I selected only studies where researchers investigated how students learned science through design. However, I was intentionally broad in my definition of the term *science*. For example, I selected studies where researchers explored either how students learned about specific scientific topics (e.g., force and motion) or general scientific categories (e.g., scientific knowledge or science content).

Third, I considered the age of the participants. Because the National Research Council's appeals for integration are around K-12 education, I selected only studies that focused on students in these grades.

Analysis

After selecting studies based on my inclusion criteria, I characterized each study along the five elements in Lehrer's (2009) design elements framework. That is, I read each study and recorded the tasks, material means, inscriptions, modes and means of argument, and activity structures. To answer my first research question (i.e., What types of activities do students engage in when participating in design-based science learning environments?), I looked across these records to identify similarities and differences within design elements and across studies. During this iterative process, I read and reread the studies I selected and created rough outlines to map the trends that emerged. I attempted to be parsimonious by collapsing any similarities into broad categories of activity for each design element and by comparing between the categories in each design element to avoid redundancy. The categories I report therefore represent a distilled account of the activities students engaged in as they participated in design-based science.

To answer my second research question (i.e., How do these activities relate to students participating in science practices and learning science content?), I looked across the family of studies where each activity was present and selected examples to illustrate how activities related to one or more of the science practices outlined in the NRC's Framework (2012), including:

- *Asking questions*: Scientists ask questions to explain phenomena.
- *Developing and using models*: Scientists develop and use models to help explain phenomena.
- *Planning and carrying out investigations*: Scientists conduct systematic investigations to test and refine theories.
- *Analyzing and interpreting data*: Scientists use tools and techniques to analyze and interpret data in search of patterns.
- *Using mathematics and computational thinking*: Scientists use mathematics and computational thinking to represent systems and make predictions.
- *Constructing explanations*: Scientists construct theories to explain phenomena.
- *Engaging in argument from evidence*: Scientists use evidence to defend their explanations of phenomena.
- *Obtaining, evaluating, and communicating information*: Scientists communicate findings to their colleagues orally and in writing.

In selecting examples, I attempted to demonstrate how different activities promoted students engaging in distinct science practices as well as how different activities fostered students learning different types of scientific content. Although I attempted to represent a range of studies when selecting my examples, it was not my intention to relate each of the studies I reviewed to each of the practices present in the NRC Framework (2012).

To answer my third research question (i.e., How do these activities align with established engineering practices?), I compared the activities I discovered to research about how practicing engineers go about "doing" engineering. To do this, I drew on information and examples from engineering education research and empirical studies of engineering. Much of this research came from outside of the field of K-12 education.

One caveat of my method is that although I set out to identify common activities throughout design-based science learning environments, the degree to which researchers reported about each of the five elements in Lehrer's (2009) framework varied considerably. A second caveat of my method is that I treated the five design elements in Lehrer's framework as discrete. In reality, tasks overlap with activity structures, which in turn overlap with inscriptions, and so on, and the learning environment emerges from the dynamic interplay among them. I address these limitations further in the discussion.

Results

Based on the criteria outlined above, I selected 21 studies to include in this review (see Table 1). The earliest of these studies was published in 1996 and the most recent was published in 2012. Participants included students ranging from first- to twelfth-grade. Typically, researchers reported working with a single intact science class, although in some instances, researchers reported working with students across different classrooms, grades, and schools. For some studies, the topic of investigation was broad. That is, some researchers reported the goal of the study was for students to learn about scientific concepts or scientific knowledge while others reported focusing on narrower topics such as simple machines or managing erosion. In addition, several researchers reported asking students to participate in multiple design contexts within the same study. For example, Sadler et al. (2000) reported asking students to participate in contexts where they designed bridge trusses, electromagnets, and wind turbines.

Finally, researchers provided different details about the study's duration. In general, researchers reported the exact length and number of class periods students spent working on the design challenge, although several researchers approximated the study's duration by describing the average amount of time they spent in a classroom across several weeks or months. To compare between studies, I expressed the duration of each study in weeks.

I present the remainder of the results in three parts. First, I sketch the prominent activities that emerged from my analysis of the design-based science literature. Second, I draw connections between the activities I identified and the science practices outlined in the NRC's Framework (2012). Third, I explain how the activities I identified align with established engineering practices. Each of these three parts addresses one of my research questions.

Table 1

Descriptive Information for the Design-Based Science Studies Included in the Review

Year	Authors	Publication Type	Grade	Sample Size	Topic of Investigation	Design Context	Duration (weeks)
1996	Roth	Journal article	4, 5	28	Materials and forces, structural strength, stability	Structures (towers)	13
1997	Penner, Giles, Lehrer, & Schauble	Journal article	1, 2	48	Model-construction and revision	Model human elbows	.5
1998	Penner, Lehrer, & Schauble	Journal article	3	17	Structure and function (biomechanics)	Model human elbows	2
1998	Middleton & Corbett	Book chapter	5, 6	16	Structural stability and forces	Model bridges	2
2000	Hmelo, Holton, & Kolodner	Journal article	6	42	Complex systems (respiratory system)	Artificial lungs	2.5
2000	Lehrer, Schauble, Carpenter, & Penner	Book chapter	2	45	Modeling, mathematization, and inscriptions	LEGO® cars and racetracks	1
2000	Sadler, Coyle, & Schwartz	Journal article	5 – 9	457	Physical science concepts	Six modules (e.g., suspension bridge challenge)	1 – 2
2001	Roth	Journal article	6, 7	26	Simple machines	Simple machines	16
2001	Seiler, Tobin, & Sokolic	Journal article	9 – 12	33	Newton's laws of motion	Model cars	1
2002	Zubrowski	Journal article	4	- -	Physical science concepts	Model windmills	- -
2003	Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntambekar, & Ryan	Journal article	6 – 8	240	Forces and motion	Vehicles and propulsion systems	8

Year	Authors	Publication Type	Grade	Sample Size	Topic of Investigation	Design Context	Duration (weeks)
2004	Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman	Journal article	9, 10	92	Scientific knowledge	Extreme structures	8
2005	Barnett	Journal article	9	25	Physics principles	Remote operated vehicles (ROVs)	23
2005	Puntambekar & Kolodner	Journal article	8	- -	Managing erosion	Stream table models	3
2005	Venville, Rennie, & Wallace	Journal article	9	6	Electrical circuits and current	Solar-powered boats	12
2008	Lehrer, Schauble, & Lucas	Journal article	6	19	Understanding of inquiry	Aquatic systems	36
2008	Mehalik, Doppelt, & Schunn	Journal article	8	1,053	Electricity concepts	Electrical alarm systems	4.5
2009	Silk, Schunn, & Strand-Cary	Journal article	8	170	Science reasoning	Electrical alarm systems	8
2010	Wendell & Lee	Journal article	3	9	Materials science practices	Model houses	4
2011	Schnittka & Bell	Journal article	8	71	Heat transfer and thermal energy	Model penguin dwellings	1
2012	Marulcu & Barnett	Journal article	5	33	Simple machines	Simple machines	4

Note. Studies are arranged chronologically. Researchers reported grade, sample size, and duration in various ways and with different detail. I attempted to standardize this information by reporting each of the grades represented, by aggregating the sample size, and by expressing the duration of each study in weeks. Missing information is denoted with dashes.

Part I: Prominent Design-Based Science Activities

I proceed by discussing the five design elements in Lehrer's (2009) framework in the following order: tasks, modes and means of argument, activity structures, material means, and inscriptions. This sequence is meant to provide organizational structure rather than to privilege one design element or activity over another. For each design element in Lehrer's (2009) framework, I first define the element and then outline the activity I identified. I follow by elaborating on each activity and citing examples of how the activity appeared in the literature. (See the Appendix for the complete record of which activities were present in each study.)

Tasks. Tasks introduce students to disciplinary concepts and practices by challenging them to pose questions, to solve problems, or to otherwise respond to a goal (Lehrer, 2009; Lehrer & Schauble, 2000). Ideally, engaging in tasks fosters students' disciplinary learning and understanding. My review of the design-based science literature revealed that while design-based science tasks ranged in difficulty and duration, most introduced students to scientific concepts and practices through designing artifacts to solve ill-structured problems framed as authentic, real-world, or ill-defined.

Solving ill-structured problems. Authentic problems, those designed to make explicit the links between students' lived experiences and the issues at hand, typically required students to design an artifact based on a perceived need in their own lives (Mehalik, Doppelt, & Schunn, 2008; Silk, Schunn, & Strand-Cary, 2009). For example, Silk et al., (2009) challenged students to design and build an alarm system based on how they might use one in their own homes. Silk et al. reported that during this task students built alarm systems to monitor objects they valued (e.g., one group of students developed a closet alarm to protect their clothes). Thus, students engaged in designing solutions to problems rooted in their own interests and experiences.

Real-world problems, those in which students considered hypothetical issues in realistic contexts, often called for students to create models or small-scale functional devices. Students then used these models and devices to explore scientific phenomena (Kolodner et al., 2003; Puntambekar & Kolodner, 2005; Marulcu & Barnett, 2012; Roth, 2001). For example, Kolodner et al. (2003) challenged students to imagine themselves as members of a team of scientists who needed to design and build a vehicle to use in an Antarctic exploration. Similarly, Roth (2001) contracted with students through a fictional company, Northern Explorations, to design and construct manual backup systems to move heavy loads over harsh terrain. In each of these examples, students went on to explore the scientific principles behind their designs.

Whether they posed authentic or real-world problems, researchers generally structured problems so that they were ill-defined (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003; Lehrer, Schauble, & Lucas, 2008; Roth, 1996). Ill-defined problems had goals that were unspecified, ambiguous, or open to interpretation. In other words, there were many ways to solve ill-defined problems. For example, Lehrer et al. (2008) challenged students to design sustainable aquatic ecosystems in one-gallon jars. Although initially an unproblematic and clear goal, students soon grappled with the idea of what it meant to be sustainable as well as with the appropriate configurations of biotic and abiotic constituents of their aquatic ecosystems.

Modes and means of argument. Modes and means of argument are the normative practices by which students use evidence and rhetoric to make and contest claims (Lehrer, 2009; Lehrer & Schauble, 2000). Modes and means of argument develop over extended activity and provide opportunities for students to build knowledge across time and settings. My review of the design-based science literature revealed two primary forms of argument: (a) students evaluated models to make evidence-based claims, and (b) students communicated claims by discussing ideas and artifacts.

Evaluating models. Researchers frequently asked students to use evidence drawn directly from their models to make claims, including assertions about the phenomena the models sought to explain (Fortus et al., 2004; Kolodner et al., 2003; Lehrer et al., 2008; Middleton & Corbett, 1998; Puntambekar & Kolodner, 2005; Sadler et al., 2000; Schnittka & Bell, 2011). For example, Fortus et al. (2004) asked students to evaluate how well model structures withstood simulated severe environmental conditions. In the simulation, students placed weights—representing large amounts of snowfall or sand from a sandstorm—on each model's roof. Students found that some models performed better than others (e.g., the roofs of some models deflected less than others). Students then used evidence about how their models performed to make claims about which designed aspects of their models were the most beneficial.

Students also generated evidence for their claims by constructing models from easily manipulated materials (Puntambekar & Kolodner, 2005; Sadler et al., 2000; Wendell & Lee, 2010). For example, Puntambekar and Kolodner (2005) challenged students to investigate the different effects of tides, currents, and waves on erosion by designing model stream tables where they could easily change the conditions. Similarly, Sadler et al. (2000) asked students to build model bridge trusses from sheets of paper. When the paper models tore, students simply replaced the model using an identical sheet of paper. In each of these cases, students explored a variety of models in a short timeframe, allowing them to collect evidence to support their claims quickly as they participated in cycles of building and evaluation.

Finally, students generated evidence for their claims by interpreting their own models (Kolodner et al., 2003; Lehrer et al., 2008; Lehrer, Schauble, Carpenter, & Penner, 2000). For example, Lehrer et al. (2008) asked students to convince their peers of the validity of their claims using evidence they collected from their one-gallon aquatic ecosystems, which served as models of a retention pond nearby the school. Because the models were extremely variable, students needed to interpret what their data meant. Thus, students not only had to have valid models but also had to convince their classmates of the validity of their claims. Some students asserted that in retrospect, their designs, although functional, were not good models of the pond because the jars were more susceptible to the effects of small variations than was the pond.

Discussing ideas and artifacts. Small-group settings were venues where students developed, shared, and modified their ideas and artifacts (Fortus et al., 2004; Hmelo et al., 2000; Kolodner et al., 2003; Lehrer et al., 2008; Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998; Roth, 1996; Silk et al., 2009). For example, Fortus et al. (2004) encouraged an open exchange of personal ideas as students worked in small groups to construct their extreme structure models. During these open exchanges, students presented possible solutions for the design challenge to their group members. Each group then contemplated and selected a solution, which they later justified in writing. Importantly, each group member had the opportunity to contrast his or her own thinking to the other group members' thinking.

Whole-group settings were also venues for students to discuss ideas and artifacts (Hmelo et al., 2000; Kolodner et al., 2003; Lehrer et al., 2008; Penner et al., 1997; Penner et al., 1998; Roth; 1996; Roth, 2001). For example, Roth (1996) reported structuring whole-group discussions so that students could compliment one another, ask questions, or give each other advice about how to improve their model towers. Additionally, Roth also asked students to share the problems they encountered and to explain the ways they solved those problems. These discussions led students to reflect on their own design solutions and to consider alternative design perspectives.

Sometimes, teachers facilitated whole-group discussions by posing questions or by reviewing the results of past design challenges (Hmelo et al., 2000; Kolodner et al., 2003; Puntambekar & Kolodner, 2005). For example, Hmelo et al. (2000) and Kolodner et al. (2003) reported structuring whole-group discussions around information recorded over the course of instruction on classroom whiteboards. This process, *whiteboarding*, allowed teachers and researchers to keep a visible record of the ideas, explanations, and issues students identified during design challenges. Each day, teachers and researchers anchored whole-group discussions in content recorded on the classroom whiteboard. Whiteboarding discussions helped students consider hypotheses, generate conjectures, and identify new explorations.

Finally, several researchers sought to make student-led presentations (i.e., instances where either a single student or a group of students presented an artifact to the class in the midst of a design challenge) a normative classroom practice (Fortus et al., 2004; Kolodner et al, 2003; Lehrer et al., 2008). For example, Fortus et al. (2004), and Kolodner et al. (2003) asked students to present throughout their challenges in pin-up sessions (otherwise known as gallery walks) where they displayed posters or artifacts under design to other members of the class. Likewise, Lehrer et al. (2008) reported asking students to present regularly to their classmates in research meetings. Research meetings had specific expectations and roles for presenters and for audience members and facilitated students defending their ideas to their classmates and to their teacher. Student-led presentations gave students opportunities to explain their own designs, to convince other students of the rationale behind their design, to ask questions of one another, and to weigh in on each other's ideas and artifacts.

Activity structures. Activity structures are the recurring instructional events designed by researchers and teachers to support learning (Lehrer & Schauble, 2000). My review of the design-based science literature revealed that one prominent activity structure was to engage students in cycles of design and redesign where they tested artifacts to the point of failure (i.e., artifacts performed incorrectly, underperformed, or became physically damaged).

Redesigning based on failure. Students sometimes designed artifacts that performed incorrectly during design challenges (Barnett, 2005; Kolodner et al., 2003; Lehrer et al., 2000; Lehrer et al., 2008; Marulcu & Barnett, 2012; Penner et al., 1997; Penner et al., 1998; Schnittka & Bell, 2011; Venville, Rennie, & Wallace, 2005). For example, Kolodner et al. (2003) asked students to design miniature vehicles that would propel themselves as far as possible. When their vehicles did not work, or did not travel a great distance, students redesigned them with the goal of increasing how far they traveled. Similarly, Schnittka and Bell (2011) investigated students' conceptions of heat transfer by challenging them to design a penguin dwelling that would prevent a penguin-shaped ice cube from melting. Some students' penguin dwellings failed, as their ice cubes melted quickly. In these instances, students subsequently redesigned their penguin dwellings to prevent the ice cubes from melting as quickly.

Other times, students built artifacts that underperformed (Sadler et al., 2000; Seiler, Tobin, & Sokolic, 2001; Zubrowski, 2002). For example, Zubrowski (2002) gave students directions to build a model windmill. This *standard model* windmill served to narrow the scope and decrease the initial difficulty of the task: to pick up as many nails as possible. This model worked, but did not work optimally. After students constructed the standard model, they tweaked the design so that it would perform better. Students' windmills failed when they did not pick up as many nails as the original model. When this was the case, students redesigned their windmills so that they would pick up more nails in future tests.

Students' artifacts also failed when they were damaged or destroyed during a test (Fortus et al., 2004; Middleton & Corbett, 1998; Sadler et al., 2000). Middleton and Corbett (1998) provided one example of this when they studied students' conceptions of stability by challenging them to create toothpick and gumdrop bridges. Students tested their bridges to failure by adding weight until they collapsed. These tests led to discussions about geometric components of the bridge that enhanced or diminished its stability. Students then redesigned their bridges based on the discussions and subjected them to further tests. Likewise, Sadler et al. (2000) challenged students to design a lightweight paper bridge truss that would support a one-kilogram weight suspended from the bottom of the truss. Trusses that could not support the weight tore. When trusses tore, students redesigned them so that they could support more weight. Students clamored to improve their bridge trusses in these tests against nature. Testing against nature was so effective at motivating students to redesign their models that Sadler et al. suggested it as in indispensible aspect of an engineering challenge.

Material means. Material means include the complete array of tools and supplies students use to accomplish a task. Because material means frame design, observation, and experiment, knowledge of a system is tied to the qualities of the material means making up that system (Lehrer, 2009; Pickering, 1995; Shapin & Schaffer, 1985). My review of the design-based science literature showed that: (a) accessing materials influenced how students designed, and (b) researchers challenged students to negotiate constraints on material means.

Accessing materials. Some researchers reported a relationship between how students designed and the types of material means they had access to while designing (Penner et al., 1997; Schnittka & Bell, 2011; Seiler et al., 2001). For example, in Seiler et al. (2001), students brought in soda bottle caps to serve as wheels for the model cars they built for investigating the physics of motion. Because few students brought in bottle caps, the teacher decided to share the bottle caps between several classes. As a result, from one day to the next, students did not have access to the same set of wheels for their models. Not having access to the same set of wheels meant students had to regularly rebuild their models to accommodate new wheels—which sometimes caused their models to function well one day and poorly the next. Seiler et al. reported that some students were so disgusted by this variation in performance, they were upset for the remainder of the project. This example demonstrates that inadequate access to material means can cause students to lose interest in the task and can hinder how they design during a project.

In another study, Penner et al. (1997) asked first- and second-graders to build models that functioned like human elbows using materials such as tongue depressors, wooden dowels, Styrofoam™ balls, balloons, and poster board strips. Penner et al. found that most students built first-generation models that captured aspects of form rather than function. That is, most models looked like an elbow but did not replicate the way an elbow worked. Penner et al. reported that even after students had opportunities to revise their models to include functional attributes, many still included perceptually similar components. Thus, students' access to material means can dictate how their initial and late-generation models look and function. It should be noted that Penner et al.'s post-instruction interviews revealed significant shifts to function over form.

A final example of when access to material means influenced how students designed comes from Schnittka and Bell's (2011) study. As summarized previously, Schnittka and Bell asked students to build model penguin dwellings that minimized heat transfer. In this study, students used tools (e.g., temperature probes and timers) to test different building materials. Students found that building using different materials resulted in different data (i.e., some materials insulated better than others). This led students to design their dwellings based on empirical findings. Because students had the opportunity to collect data about how different materials functioned, they were able to use that data to inform their design decisions.

Negotiating constraints. Researchers challenged students to negotiate constraints by limiting the quantity of materials students could use during a design challenge (Roth, 1996; Schnittka & Bell, 2011; Zubrowski, 2002). For example, Roth (1996) supplied students with a fixed amount of cardboard and glue to build model bridges. Similarly, Schnittka and Bell (2011) set up an economic scheme whereby students built model penguin dwellings on an imaginary budget. In both cases, students dealt with researcher-imposed limits on material means.

Another method researchers used to introduce constraints was to intentionally supply students with materials that carried inherent constraints (i.e., the properties of the materials themselves limited what was possible for students to construct; Middleton & Corbett, 1998). For example, in Middleton and Corbett (1998), students learned about structural stability as they designed and built toothpick and gumdrop bridges. Researchers directed students to maximize the amount of weight their bridges could support while minimizing the number of toothpicks and gumdrops they used. In this case, students who connected their toothpicks and gumdrops together in triangular rather than rectangular constructions increased the load bearing capability of the bridge while simultaneously reducing the amount of materials (left diagram, Figure 1).

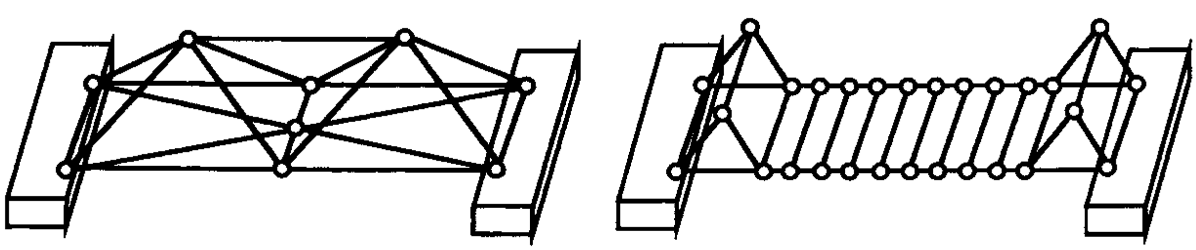

Figure 1. The triangular connections used in the bridge on the left maximize its load bearing capability while minimizing its materials. Figure adapted from Middleton and Corbett (1998).

Finally, researchers introduced constraints by restricting where students began the design process (Zubrowski, 2002; Sadler et al., 2000). For example, Zubrowski (2002) supplied students with a model windmill. As described previously, Zubrowski called this the standard model. Each standard model was assembled from the same components and worked reasonably well. Likewise, Sadler et al. (2000) supplied students with a model electromagnet. The electromagnet was pre-fabricated and worked acceptably—but not ideally. Thus, in both cases, researchers constrained how students designed by giving them pre-made functioning models.

Inscriptions. Inscriptions include figures, diagrams, and written artifacts that represent entities, relationships, or theoretically important aspects of the world; they can be manipulated, combined, and can travel across space and time (Latour, 1990, 1999; Lehrer & Schauble, 2002). Researchers have found that students learn through producing, evaluating, and revising inscriptions as they seek to explain phenomena (diSessa, 2004; diSessa & Sherin, 2000; Lehrer et al., 2000). My review of the design-based science literature revealed that students kept written records to predict what might happen during, or to explain what happened after, a design challenge.

Keeping records. Researchers frequently asked students to record inscriptions as written text in some type of notebook (Barnett, 2005; Kolodner et al., 2003; Puntambekar & Kolodner, 2005; Roth, 1996; Wendell & Lee, 2010). For example, Roth (1996) asked his students to document plans and reflections in their engineering logbooks as they designed model buildings and bridges. Similarly, Puntambekar and Kolodner (2005) and Kolodner et al. (2003) asked students to respond to prompts in design diaries that were intended to support students' reasoning as they designed stream tables and air propelled model vehicles, respectively. Likewise, Wendell and Lee (2010) integrated data recording and reflective prompts into workbooks to help students keep a record of tests and test results as they designed model LEGO® houses.

In addition to producing written text, students also kept records by creating a range of drawings (Fortus et al., 2004; Mehalik et al., 2008; Zubrowski, 2002). For example, Zubrowski (2002) asked students to develop sketches during the design process while Fortus et al. (2004) asked students to produce cut-away diagrams and technical drawings of their proposed designs. In an explicit attempt to ground students' inscriptions in an engineering context, Mehalik et al. (2008) asked students to create systems diagrams that resembled the figures and illustrations systems engineers use in their everyday work. Mehalik et al. reasoned that by asking students to produce these types of diagrams it would engage them in what they considered an authentic engineering activity.

Researchers also reported asking students to keep records of their design activity using a hybrid approach where they produced both written text and drawings (Kolodner et al., 2003; Sadler et al., 2000; Schnittka & Bell, 2011). For example, Sadler et al. (2000) and Schnittka and Bell (2011) asked students to create storyboards modeled on Disney's studio method for developing a cartoon. Students used storyboards to document how they solved a design challenge over time by writing and animating the complete sequence of events. Sadler et al. reported that storyboards were a powerful record keeping technique as long as they were purposefully used as a resource in reflective activities.

Summary: Prominent design-based science activities. To summarize, seven prominent activities emerged from my analysis of design-based science learning environments. Although not all the studies I reviewed exemplified each activity, many studies touched on multiple activities in one way or another. The seven activities I identified included:

- *Solving ill-structured problems*: Tasks challenged students to solve problems. This activity was exemplified by studies in which researchers posed scenarios that required students to design artifacts to investigate and solve design challenges.
- *Evaluating models*: Students evaluated models to make evidence based claims. This activity was exemplified by studies in which students analyzed and evaluated models to make a claim about their own model, about someone else's model, or about a phenomenon the model represented.
- *Discussing ideas and artifacts*: Students communicated by discussing ideas and artifacts. This activity was exemplified by studies in which researchers reported intentionally planning for students to discuss ideas and artifacts in various settings.
- *Redesigning based on failure*: Students engaged in cycles of design and redesign based on testing artifacts to the point of failure. This activity was exemplified by studies in which researchers required students to test their models to the point of physical failure. In these instances, artifacts failed if they broke, collapsed, or tore.
- *Accessing materials*: Differential access to material means influenced how students designed. This activity was exemplified by studies in which researchers attributed an artifact's design to the materials students had access to when designing.
- *Negotiating constraints*: Researchers introduced constraints on material means to prompt students to negotiate those constraints when designing. This activity was exemplified by studies in which researchers reported limiting the quantity of materials available to students solving a design challenge.

- *Keeping records*: Students produced inscriptions to keep records. This activity was exemplified by studies in which students produced inscriptions in a workbook or a log with the intention of revisiting the inscriptions at various points during instruction.

Part II: Participating in Science Practices and Learning Science Content

In this section, I explain how the seven activities I identified in part one relate to the eight science practices (i.e., asking questions; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations; engaging in argument from evidence; and obtaining, evaluating, and communicating information) outlined in the NRC's Framework (2012). In addition, I describe how participating in these activities facilitated students learning a range of science content.

Solving ill-structured problems. Solving ill-structured problems engaged students in the scientific practice of *asking questions*. For example, while building a model artificial lung, Hmelo et al.'s (2000) students generated their own learning issues related to the broader activity. That is, they developed small-scale questions to investigate under the umbrella of the larger design challenge. Examples of these questions included: How much oxygen does a person need? How much oxygen can the lungs take in? and How is oxygen processed in the lungs? Using information gathered from pre- and post-tests, artifact analyses, and individual student interviews, Hmelo et al. found that asking questions and solving problems contributed to students developing sophisticated understandings of the structural, behavioral, and functional relationships within the respiratory system.

Likewise, Kolodner et al. (2003) promoted students asking questions by developing mini-challenges where students formulated hypotheses to address the issues they encountered while working toward the larger goal of designing and building a model vehicle capable of traveling quickly over hilly terrain. During these mini-challenges, students investigated scientific concepts such as mass, friction, gravity, and inertia. Additionally, using pre- and post-performance assessments designed to measure various dimensions of the learning environment, Kolodner et al. reported that students who were involved in solving design challenges checked their work, designed fair tests, planned experimental designs, and used evidence to justify their claims as well or better than comparison students exposed to a more traditional curriculum.

Evaluating models. Evaluating models led to students *developing and using models* and *constructing explanations*. For example, in Penner et al. (1997), students built model elbows to help explain how their own elbows functioned. Penner et al. found that young children were capable of developing model-evaluation skills and that building and revising models helped children identify constraints on motion as important features governing how elbows functioned. Additionally, by comparing the results of interviews of students who had participated in the modeling activity with the results of interviews of students who had not participated in the modeling activity, Penner et al. found that, compared to their non-modeling peers, students who built and revised models understood the modeling process in a more sophisticated way.

Discussing ideas and artifacts. Discussing ideas and artifacts led to students *engaging in argument from evidence*. For example, in Lehrer et al. (2008), students' discussions of their one-gallon jar models of aquatic ecosystems often required them to defend the soundness of their research design to other members of the class. Using a combination of classroom observation and semi-structured individual interviews, Lehrer et al. reported that regular participation in research meetings caused students to grow increasingly aware of the importance of using evidence to support claims. Furthermore, Lehrer et al. found that students also became adept at asking and answering questions about the adequacy of their own models as well as those of their classmates. These results align with the understanding that models themselves are forms of argument (Bazerman, 1988; Latour, 1999; Lehrer & Schauble, 2000).

In addition to helping students engage in argument from evidence, discussing ideas and artifacts led to students *evaluating and communicating information*. For instance, using classroom observation, Fortus et al. (2004) reported that participating in small-group discussions allowed students to compare and contrast possible solutions to design challenges. Similarly, Roth (1996), also relying on classroom observations, reported that by engaging in whole-group discussions, students had opportunities to share solutions to the problems they encountered while building model structures. Both Fortus et al. and Roth agreed that interactions within and between groups helped knowledge circulate throughout the classroom—indicating the importance of whole- and small-group discussions for communicating information.

Redesigning based on failure. Redesigning based on failure engaged students in the scientific practice of *planning and carrying out investigations*. For example, Sadler et al. (2000) noted that students who failed during their initial attempts at designing paper bridge trusses capable of supporting a one-kilogram weight went on to complete redesigns where they planned to alter important features of the trusses they designed. For instance, students frequently altered parts of the truss that were under the greatest stress during the test, such as the load-bearing points. Furthermore, using pre- and post-tests designed to measure science process skills, Sadler et al. found that when students participated in the design and redesign of paper bridge trusses, their abilities to judge the quality of an experimental design increased significantly.

Similarly, Schnittka and Bell (2011) engaged students in planning and carrying out investigations by asking them to redesign penguin dwellings that failed to prevent a penguin-shaped ice cube from melting. After initial tests to gauge how well their penguin dwellings worked, students planned revisions and made improvements before carrying out further investigations. Schnittka and Bell hypothesized that designing and redesigning penguin dwellings contributed to changes in students' initial (and incorrect) conceptions about heat transfer. Using pre- and post-tests designed to measure students' conceptions of heat transfer, Schnittka and Bell found that students who participated in design and redesign activities, combined with targeted demonstrations intended to disrupt students' incorrect conceptions about heat transfer, showed significant gains in their understanding of aspects of heat transfer and thermal energy such as conduction, insulation, radiation, and convection.

Accessing materials. Access to materials also led to students *planning and carrying out investigations*. For example, in an activity in which children explored force and motion concepts by designing LEGO® cars so that they traveled down a ramp as fast as possible, Lehrer et al. (2000) problematized aspects of the design challenge by providing students with materials that required them to operationalize and measure attributes of the situation such as speed, steepness, and the nature of a trial. Lehrer et al. found that when faced with operationalizing and measuring these attributes, students proposed investigations to determine which cars were faster (e.g., by pitting the cars against one another on the same track rather than racing them individually) and students proposed methods to determine what constituted a fair trial (e.g., by selecting the median value of five races as an accurate representation of a car's speed).

Negotiating constraints. Negotiating constraints engaged students in the scientific practices of *planning and carrying out investigations* and *developing and using models*. For example, Zubrowski (2002) supplied students with a standard model windmill that functioned adequately but not optimally. Confronted with the issue of how to improve the model, students performed systematic investigations in which they changed one variable or another (e.g., the number of blades, the surface area of the blades, the pitch of the blades) and conducted tests to evaluate the results. Zubrowski found that by operating on the standard model in an effort to improve its function, students had opportunities to investigate physical science concepts such as energy transformation, work, and power.

Keeping records. Keeping records engaged students in the scientific practice of *analyzing and interpreting data*. For example, prior to engaging in a design challenge in which they built a model bridge, Middleton and Corbett (1998) asked students to produce drawings and inscriptions to help them make sense of how different three-dimensional shapes would respond to applications of force. Using information gathered from individual interviews, Middleton and Corbett found that producing and analyzing inscriptions aided students in understanding conceptions of stability, including the transmission of force. Middleton and Corbett also noted that analyzing inscriptions helped some students understand that structures built from triangular constructions were more stable than those built from rectangular constructions.

In addition to helping students engage in the practice of analyzing and interpreting data, keeping records promoted students' emergent *use of mathematics and computational thinking*. For instance, Penner et al. (1998) conducted a study in which researchers asked students to complete a biomechanical investigation of a model elbow. Using classroom observations, Penner et al. found that during the investigation, students made generalizations about leverage based on the mathematical relationships in the data they collected. For example, students recorded, summarized, and re-represented data in the form of charts and graphs in order to draw conclusions about the biomechanical properties of the model elbow.

Summary: Participating in science practices and learning science content. To summarize, each of the seven activities I identified as prominent features of design-based science learning environments related to one or more of the eight science practices outlined in the NRC Framework (2012). Additionally, students had opportunities to learn a range of scientific content demonstrated by a variety of forms of evidence (e.g., pre- and post-test comparisons, individual interviews, artifact analysis, classroom observations, and performance assessments).

Part III: Aligning Activities With Engineering Practices

In this section, I explain how the activities I identified in part one align with professional engineering practices. Throughout the section, I draw on examples from the engineering education literature as well as from studies that investigated workplace engineering to illustrate the connections between the activities I identified and a range of engineering practices.

Solving ill-structured problems. Organizing design-based science tasks around authentic, real-world, and ill-defined problem solving approximates the types of problems practicing engineers routinely attempt to solve. That is, engineers rarely face well-defined problems that have a single correct answer that can be judged as right or wrong (Jonassen, 2000). Instead, engineers typically face problems that are complex, have multiple solution paths, and possess multiple criteria for evaluating those solutions (Shin, Jonassen, & McGee, 2003, Katehi et al., 2009).

In addition, by engaging students in tasks in which they designed solutions to problems, students directly experienced *iterative refinement*—the successive design and redesign of an artifact (Katehi et al., 2009). For example, Hmelo, et al. (2000), Kolodner et al. (2003), and Puntambekar & Kolodner (2005) used Learning By Design™ (LBD) to motivate students to iteratively refine artifacts (Figure 2). In order to solve a design challenge (e.g., building a vehicle's propulsion system), students engaged in cycles of planning and designing, building and testing, and analyzing and explaining. This process triggered cycles of investigation and exploration where students asked questions, scrutinized concepts, and analyzed results. Together, these cycles drove the need for students to iteratively refine their artifacts.

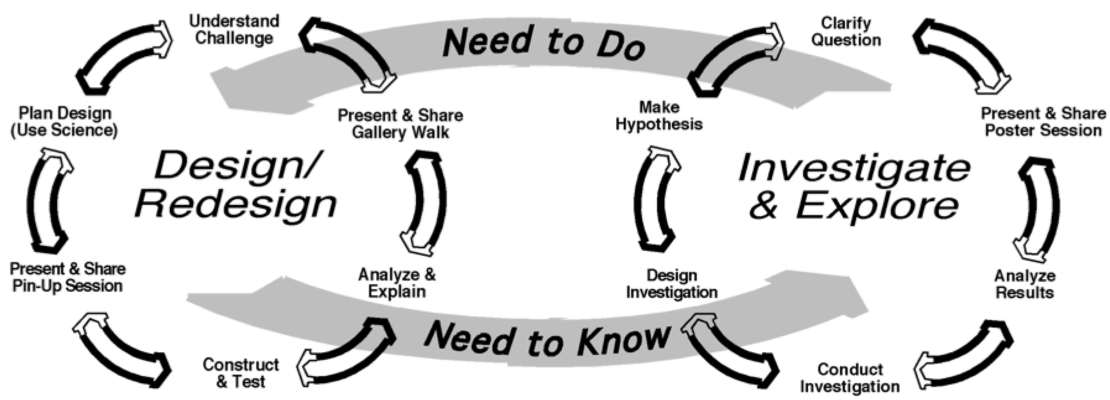

Figure 2. The Learning by Design learning cycle (adapted from Kolodner et al., 2003).

Engineers iteratively refine artifacts based on unforeseen constraints and unanticipated difficulties. Often, these constraints and difficulties require engineers to solicit outside assistance, consider diverse forms of feedback, and enter into cycles of design and redesign (Katehi et al, 2009). Because engineers change their minds and make on-the-fly adjustments while in the act of designing, it is difficult to draw a metaphorical straight line from where an engineer began to where she ended. Hence, when engineers design, they typically do so in a non-linear way (Lewis, 2006). Because they required students to solve problems by moving towards their goals incrementally and indirectly, design-based science tasks approximated the conditions under which practicing engineers engage in non-linear design. In turn, engaging in non-linear design promoted students participating in further cycles of iterative refinement.

Finally, in the design-based science literature reviewed here, opportunities for iterative refinement also led students to participate in optimization. Optimization is the stage in the design process in which an engineer maximizes the functionality of the design (ITEA, 2000). Optimization is important in professional engineering because it is the means by which engineers "enhance or make small gains in desirable characteristics," (ITEA, 2000, p. 42). Approximating the work of professional engineers, students regularly attempted to optimize the artifacts they built during design challenges by making minute alterations to the artifact, then testing the effects of the alteration (Fortus et al., 2004; Mehalik et al., 2008; Sadler et al., 2000; Silk et al., 2009; Zubrowski, 2002).

Evaluating models. Although evaluating models to generate evidence for a claim approximates the way practicing scientists use models (NRC, 2012), it fails to adequately capture the way practicing engineers use models. Although both scientists and engineers use models in their everyday work, there are subtle differences in the ways scientists and engineers evaluate those models. For example, while scientists often evaluate models to help explain phenomena (Gooding, 1990), engineers typically evaluate models to examine how well they satisfy the needs of a client or a consumer (Otto & Antonsson, 1991). In other words, scientists primarily evaluate models to help explain the world around them, while engineers primarily evaluate models as a step toward developing working products that fulfill a specific function. As a result, engineers tend to evaluate models to compare attributes, explore details about feasibility and appearance, or to facilitate early testing of a function (Gebhardt, 2003).

Central to the way engineers evaluate models is the concept of considering trade-offs (Katehi et al., 2009; Otto & Antonsson, 1991). When engineers consider trade-offs, they weigh design decisions about the different aspects of a model to determine which of the final product's attributes to maximize or minimize. For example, an engineer might design a model that sacrifices aesthetic aspects and emphasizes functional aspects in order to maximize a product's usability. Likewise, an engineer might design a model from radically different materials, thereby increasing the cost of the project, in order to increase its durability. Both of these examples demonstrate that engineers must systematically consider trade-offs for a range of decisions during the design process and that each of these decisions influences the final product. These opportunities were not explicitly featured in design-based science learning environments reviewed here.

Discussing ideas and artifacts. The types of discussions found in the design-based science learning environments I reviewed engaged students in forms of rhetoric that parallel the forms of rhetoric practicing engineers use to communicate in the workplace. For example, during discussions (e.g., whole-group, small-group, gallery walks, and research meetings), students shared their opinions, voiced agreement and disagreement, negotiated and argued with peers, questioned decisions, recommended changes, and justified design decisions. Each of these modes of discourse represents a rhetorical device valuable for making or contesting claims.

Importantly, practicing engineers use many of the same rhetorical devices in their own work. For example, Darling and Dannels (2003) collected information from 123 active and retired engineers to assess the importance of speaking and writing in industrial engineering contexts. Darling and Dannels found that effectively communicating information to engineering and non-engineering audiences was a large part of what engineers did on a daily basis. Furthermore, they noted that engineers consistently relied on forms or rhetoric such as questioning and negotiating when communicating with individuals and small groups.

Like Darling and Dannels (2003), Winsor (1998) examined how written documents and oral interactions helped engineers “do engineering” (p. 345). To do this, Winsor shadowed three different engineers working at an agricultural equipment manufacturing company. Winsor found that the individuals she shadowed built consensus by discussing inscriptions and artifacts with other engineers. Additionally, Winsor found the engineers exercised rhetorical devices such as evidence-based argument to persuade management that their solutions were valid.

The engineering community has also recognized how important communication is in professional engineering. For example, in their 2004 publication, *The Engineer of 2020*, the National Academy of Engineering (NAE) described several skills they believed future engineers would need. The NAE's description outlined that in the future, engineers should be able to work in teams and be receptive to change while being mutually respectful of one another. Additionally, the NAE noted that engineers of the future should be able to communicate effectively between diverse stakeholders involved in the projects they undertake (Clough, 2004).

Like the NAE, the Accreditation Board for Engineering and Technology (ABET), the entity responsible for accrediting higher education schools of engineering, has outlined that engineering students must have the opportunity to productively work on interdisciplinary teams and to communicate with engineering professionals (ABET, 2011). Thus, there is growing consensus that it is important for aspiring engineers to communicate clearly and effectively among diverse groups, much like students did in the design-based science literature I reviewed.

Redesigning based on failure. Practicing engineers deal with failure whenever artifacts malfunction or break down (Liao, Zhang, & Mount, 2000). When artifacts fail, engineers investigate what caused the failure. These investigations lead to cycles of design and redesign in which engineers work to prevent similar types of failures from occurring in the future. This process is called troubleshooting. Troubleshooting leads engineers to refine their problem solving skills and their technical knowledge of the system under study (Jonassen & Hung, 2006). Design-based science activities requiring students to test artifacts to the point of failure approximated the conditions under which practicing engineers engage in troubleshooting. During these activities, students had opportunities to investigate why artifacts failed and how redesigning them would ensure that they performed properly in the future.

Engineering educators advocate including troubleshooting in K-12 engineering education because it mimics how practicing engineers solve problems. For example, Brophy et al. (2008) recommended that students engage in the practice of troubleshooting because it contributes to how engineers develop new devices, processes, and infrastructure. Moreover, according to the International Technology Education Association (ITEA), troubleshooting plays an important role in the design process (ITEA, 2000). The ITEA notes that students learning about the design process should engage in troubleshooting in order to experience how engineers diagnose and fix problems in simple and complex systems (ITEA, 2000).

Accessing materials. For the most part, design-based science researchers asked students to begin designing from scratch, using either researcher-supplied or student-supplied material means. For example, Hmelo et al. (2000) provided students with balloons, clay, and 2-L bottles to build artificial lungs. Although designing from scratch replicates the way some engineers work, many engineers begin by redesigning or by deconstructing existing artifacts to get a sense of what the artifact does and how the artifact works (Otto & Wood, 1998; Wood, Jensen, Bezdek, & Otto, 2001). This practice—known as reverse engineering—requires an engineer to ascertain how an artifact works by analyzing, inspecting, and testing its structure and function.

Reverse engineering activities give students the opportunity to discover processes and techniques that past engineers have used to solve design problems. Although reverse engineering was not present in the K-12 studies I reviewed, it has been used successfully in studies of post-secondary engineering students. For example, Sheppard (1992) reported introducing the design process to her undergraduates by asking them to perform *mechanical dissections* of artifacts (e.g., fishing reels, inkjet printers, and ten speed bicycles). Sheppard's students disassembled an existing artifact and then examined how the artifact worked by predicting, observing, analyzing, testing, and gathering information about its structure and function. These activities allowed students to see firsthand the designed components engineers used to make the artifact function.

Researchers have also used reverse engineering activities as a way to help students understand why designed solutions work (Otto & Wood, 1998; Wood et al., 2001). For example, Wood et al. (2001) reported about a project where undergraduate students redesigned an industrial product they found interesting. Once students chose a product, they examined and used the product, collected information from consumers about the product, compared the product to similar products, and predicted how the product worked. Students followed by disassembling the product and developing a report detailing how to improve the product. This series of activities gave students a broad understanding of the nature of an industrial product as well as a nuanced understanding of why the product worked.

Negotiating constraints. Constraining the material means students can use during a design challenge helps engage them in the practice of designing under constraints (Katehi et al., 2009; ITEA, 2000), which is an important aspect of professional engineering. For example, in their study of how engineers solved workplace problems, Jonassen, Strobel, & Lee (2006) reported that engineers often designed under a variety of constraints (e.g., money, time, and safety) imposed by clients, corporations, and government entities. By limiting the quantity of materials students could use during design challenges, design-based science researchers replicated the monetary and material constraints practicing engineers face when designing.

However, one problem with limiting the quantity of money or materials students can use during a design challenge is that practicing engineers do not always work within the constraints of limited supplies. That is, engineers commonly use more materials than they expect to use (e.g., the iron bridge in Shropshire, England—the first metal bridge in the world—required 20 percent more iron than predicted) and go over budget (e.g., the Sydney opera house was approximately 14 times more expensive to build than anticipated). Interestingly, Roth (1996) demonstrated that this held true with elementary-age students when he observed that even when working under teacher-imposed constraints, students not only successfully argued for more materials, but also furtively repurposed ordinary classroom objects as building materials.

In addition to imposed constraints, engineers must also consider inherent constraints when designing. These inherent constraints bind engineers differently than imposed constraints. That is, inherent constraints often determine the limits of what is possible for an engineer to design (Ashby, 1999). For example, engineers who design concrete structures are constrained by concrete's limited tensile strength. Yet, concrete has a high compressive strength. Hence, concrete's inherent constraints make it a good material to use for building some structures and a poor material to use for building others. Middleton and Corbett (1998) illustrated how introducing constraints based on the properties of the materials (i.e., toothpicks and gumdrops) and based on the physics and mathematics inherent in the task (i.e., bridge-building) replicated how practicing engineers consider inherent constraints when designing artifacts.

Finally, by requiring students to start with models that worked adequately, but not optimally (e.g., Sadler et al., 2000; Zubrowski, 2002), researchers decreased the scope and complexity of design tasks. That is, when researchers challenged students to improve models rather than to build them from scratch, they narrowed the task's focus. Similarly, engineers often work within microcosms where they seek to improve artifacts and processes (Gebhardt, 2003;

Hitchins, 2007). Consequently, restricting material means to control where students begin designing simulates one way engineers design under constraints.

Keeping records. Although practicing engineers do routinely produce inscriptions to keep records, they also produce and evaluate inscriptions to solve the problems they encounter during the design process. Several researchers have documented how inscriptions help engineers solve problems (Henderson, 1991; Jonassen et al., 2006; Simon, 1999; Stevens & Hall, 1998, Winsor, 1998). For example, Jonassen et al. (2006) interviewed over 100 practicing engineers to elicit information about how they solved workplace problems. These engineers reported producing multiple types of inscriptions when designing (e.g., drawings, charts, computer-aided design (CAD) renderings, and EXCEL documents). Jonassen et al. determined that production of, and access to, a variety of inscriptions helped engineers solve complex workplace problems by allowing them multiple ways to represent and reason about the problem.

In another study, Stevens and Hall (1998) documented an *in situ* case of two civil engineers working to make revisions to a roadway design plan for a northern California neighborhood. Throughout their interaction, the two engineers evaluated three CAD inscriptions: (a) a plan view (showing the layout of the land), (b) a profile view (showing specific elevations), and (c) a section view (showing vertical slices of the roadway) to solve the problem of how to grade the site correctly and remain within budget. Stevens and Hall concluded that the engineers evaluated multiple inscriptions in coordination to solve the problem. Importantly, indexing inscriptions with different views helped engineers visualize and discuss the problem.

In addition to using inscriptions to solve problems, engineers also use them to mathematize aspects of design challenges (Gainsburg, 2007; Hall, 1999). Mathematization is the progressive description and re-description of a system in terms of mathematical objects, relations, and generalizations (Kline, 1980; Lynch, 1988). Often, when engineers mathematize aspects of design challenges, they do so by producing or evaluating inscriptions. For example, Gainsburg (2007) described how structural engineers sketched architectural elements to determine the conditions under which they would fail. The sketches the engineers produced contained graphs, force diagrams, and mathematical calculations. Similarly, Hall (1999) described how architects and engineers grounded discussions of important mathematical relationships (e.g., demand/capacity ratio—the measure of a building's resistance to shaking) in different inscriptional forms (e.g., architectural plans and city code books) as they planned to seismically retrofit a public library. In both cases, engineers used inscriptions to mathematize aspects of the design challenge to assist them in reasoning about the artifact under design. Comparatively, there are few examples from the K-12 design-based science literature where students use inscriptions to solve problems or mathematize aspects of a design challenge.

Summary: Aligning activities with engineering practices. In summary, some attributes of design-based science learning environments align well with existing engineering practices (e.g., redesigning based on failure aligns well with the practice of troubleshooting) while other attributes of design-based science learning environments do not align well with existing engineering practices (e.g., practicing engineers tend to evaluate models in different ways and for different purposes than are emphasized in design-based science learning environments).

Discussion

Recent appeals from the NRC espouse integrating K-12 science and engineering to improve the interconnectedness of pre-college STEM education. In this light, I examined how design-based science learning environments promoted science and engineering practices in an effort to inform the development of integrated learning environments. Using Lehrer's (2009) design elements framework to structure the review, I showed how design-based science learning environments engaged students in seven prominent activities, including: solving ill-structured problems, evaluating models, discussing ideas and artifacts, redesigning based on failure, accessing material, negotiating constraints, and keeping records. These activities supported a range of science and engineering practices (e.g., asking questions, engaging in argument from evidence, iterative refinement, and optimization). Moreover, I showed that activities led to students learning about a range of science content. Finally, I demonstrated that design-based science learning environments do *not* currently support a subset of engineering practices (e.g., considering trade-offs, reverse engineering, and mathematization).

Even though some engineering practices are not currently supported in design-based science learning environments, it seems possible to develop integrated learning environments so they conserve the science and engineering practices already present in design-based science learning environments and foster engineering practices that are not currently supported in design-based science learning environments. For example, presently, design-based science learning environments place a higher value on aspects of how scientists evaluate models rather than on aspects of how engineers evaluate models. As a result, students rarely have the opportunity to evaluate models as an engineer might. Highlighting opportunities for students to consider trade-offs as they evaluate models may help integrated learning environments replicate the conditions under which practicing engineers evaluate models.

Furthermore, developing integrated learning environments so that students evaluate models in ways that mirror how practicing engineers evaluate their own models may help make students aware of (a) when they consider trade-offs, (b) why they consider trade-offs, and (c) what attributes of their models those trade-offs maximize or minimize. Gainsburg (2007) refers to this as *engineering judgment*—the characteristic that engineers use to judge the soundness of a theory or the practicality of a design. Students who consider trade-offs exercise aspects of engineering judgment by explicitly considering how the trade-offs they make affect the artifacts they design. This shift may help integrated learning environments mimic the conditions under which practicing engineers consider trade-offs in their everyday work. For example, when students build a model to satisfy a design challenge, rather than asking them to judge the model based on how well it explains a phenomenon, researchers might consider asking students to identify a number of trade-offs they deliberated while designing and to explain how the design decisions they made maximized or minimized different attributes of the model.

In addition to highlighting engineering judgment, incorporating reverse engineering activities into integrated learning environments may give students the opportunity to discover processes and techniques that past engineers have used to solve design problems. Because reverse engineering is a common and time-tested engineering practice (Boyne, 2009; Polybius, trans. 2010) and because reverse engineering activities allow engineers to ground their design decisions in existing artifacts, incorporating reverse engineering activities into integrated learning environments may give students the opportunity to explore structural and functional relationships when designing artifacts. Furthermore, it may be possible for K-12 students to reverse engineer commonplace items, which have been described as the best items for young students to learn about technology (Benenson, 2001). For example, Benenson (2001) suggests designing or redesigning using simple artifacts like shopping bags because students have knowledge of the artifact and have access to multiple inexpensive examples.

Finally, asking students to record written text and drawings before or after a design challenge does not always require students to evaluate those inscriptions to solve design problems. Thus, student-produced inscriptions tend to live in notebooks that have no direct bearing on the design problems at hand. Developing integrated learning environments so that students engage in the production and evaluation of inscriptions to solve problems, and so that students develop a need for such inscriptions, may allow students to experience how practicing engineers use inscriptions to problem solve when designing. Also, although design-based science researchers have begun to explore the link between mathematization and the production and evaluation of inscriptions (e.g., Lehrer et al., 2000; Middleton & Corbett, 1998; Penner et al., 1998), researchers generally do not ask students to mathematize aspects of design challenges in design-based science learning environments. Linking mathematization to the production and evaluation of inscriptions so that children can reason about the underlying physical and mathematical relationships within the artifact may help promote the types of mathematical reasoning in which practicing engineers engage in their everyday work.

Limitations

This review has several limitations. First, my method for finding common activities in design-based science learning environments depended on researchers reporting about each of Lehrer's (2009) design elements in detail. In actuality, researchers reported less information about some of these design elements than others. For example, while researchers generally explained the tasks they employed, they typically did not provide as much information about why they chose to use the material means they selected. Because not all researchers reported about each of the five elements in Lehrer's (2009) framework in similar detail, it is possible that some of the activities I identified are either underrepresented, overrepresented, or that some activities are missing entirely. Second, I considered the five elements in Lehrer's (2009) framework as discrete. Treating these elements of the learning ecology as discrete artificially reduces the complexity of the learning environment. In reality, activity structures, inscriptions, modes and means of argument, material means, and tasks all influence one another. Hence, separating the characteristics of one element of the learning ecology from another serves to oversimplify many of the complex relationships within the learning environment.

Despite these limitations, this review highlights the expanded responsibilities science teachers will assume as they transition to teaching based on the NGSS (2013). Specifically, science teachers will be responsible for instructing students how practices relate to science and engineering learning goals and habits of mind. This new responsibility provokes several concerns, including: (a) What are the most important science and engineering practices teachers should emphasize? (b) Do science teachers have sufficient engineering backgrounds to link practices to engineering content? and (c) What structures are in place to support science teachers as they take up these new responsibilities? In short, this review underscores the importance of investigating how to support science teachers as they transition to teaching based on the NGSS.

In addition, this review pinpoints several broad directions for future research. For example, the review highlights the limited research on how professional engineers participate in disciplinary practices. Further research on this topic may promote the development of a refined cannon of core engineering practices—an aspect of engineering education that is currently missing (Katehi et al., 2009; NRC, 2010). The review also illustrates the dearth of research around how K-12 students participate in engineering practices in design contexts. Performing additional research on how students engage in engineering practices such as considering trade-offs, reverse engineering, and mathematizing aspects of design challenges may assist educators and researchers as they work to design for students to participate in key engineering practices in integrated learning environments.

Finally, my investigation of how design-based science activities aligned with science and engineering practices illustrated that sometimes similar practices serve unique epistemic functions (e.g., evaluating models). Conflicts in practice such as these provoke difficult to answer questions; for instance, How should educators balance the different goals of similar yet distinct practices? As the push towards integrated STEM education continues, providing explicit access to students about significant epistemic differences in how engineers and scientists practice may be as important as seeking productive synthesis across practices. As well, resolving conflicts in practice between STEM disciplines will become an important issue to consider in order to adroitly integrate science, technology, engineering, and mathematics.

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Appendix

Activities Present in Design-Based Science Studies

Study	Tasks	Modes and means of argument		Activity structures	Material means		Inscriptions
	Solving problems	Evaluating	Discussing	Redesigning	Accessing materials	Negotiating constraints	Keeping records
Roth (1996)	X	X	X	X	X	X	X
Penner et al. (1997)		X	X		X		
Penner et al. (1998)	X	X	X		X		X
Middleton & Corbett (1998)		X		X	X	X	X
Hmelo et al. (2000)	X		X		X		
Lehrer et al. (2000)	X	X	X	X	X	X	X
Sadler et al. (2000)	X	X		X	X	X	X
Roth (2001)	X	X	X	X	X		X
Seiler et al. (2001)			X	X	X		
Zubrowski (2002)		X	X	X	X	X	X

	Tasks	Modes and means of argument		Activity structures	Material means		Inscriptions
Study	Solving problems	Evaluating	Discussing	Redesigning	Accessing materials	Negotiating constraints	Keeping records
Kolodner et al. (2003)	X	X	X	X	X		X
Fortus et al. (2004)	X	X	X	X	X	X	X
Barnett (2005)	X	X	X	X			X
Puntambekar & Kolodner (2005)	X	X	X	X			X
Venville et al. (2005)				X	X	X	X
Lehrer et al. (2008)	X	X	X	X	X	X	X
Mehalik et al. (2008)	X	X	X		X	X	X
Silk et al. (2009)	X	X	X	X	X	X	X
Wendell & Lee (2010)	X	X		X	X	X	X
Schnittka & Bell (2011)	X	X	X	X	X	X	X
Marulcu & Barnett (2012)	X		X	X			X

CHAPTER III

BRINGING CHILDREN "INTO THE FOLD": LEARNING TO PARTICIPATE IN ENGINEERING PRACTICES BY DESIGNING PAPER POP-UP BOOKS

Recent efforts to evaluate the state of K-12 engineering education in the U. S. indicate that capitalizing on relations between engineering content and current STEM (science, technology, engineering, and mathematics) standards may result in richer STEM learning by children of all ages (Brophy, Klein, Portsmore, & Rogers, 2008; Douglas, Iversen, & Kalyandurg, 2004; ITEA, 2000; Katehi, Pearson, & Feder, 2009; Lewis, 2006; Pearson & Young, 2002). In 2010, the National Research Council's (NRC) Committee on Standards for K-12 Engineering Education ratified this viewpoint by recommending that standards *not* be developed for K-12 engineering education. Instead, the NRC suggested teaching engineering concepts, skills, and practices by integrating them into existing STEM standards (NRC, 2010), as is evident in the Next Generation Science Standards (NRC, 2012).

The shift towards integrated science and engineering education is based on the understanding that both disciplines share a collection of interconnected practices, and that when children engage in these shared practices, they have opportunities for interdisciplinary learning (NRC, 2012). Adopting this perspective underscores the importance of conducting research to better understand how children engage in engineering practices and highlights the significance of investigating how to integrate these practices into science education. However, this perspective also generates concerns about how to bridge the gap between comparable practices across disciplines. For example, although scientists and engineers each evaluate models, they often do so to accomplish different goals. While scientists typically evaluate models to help explain phenomena (Gooding, 1990), engineers often evaluate models to judge how well they satisfy the needs of a client (Otto & Antonsson, 1991) or to provide access to objects and relations in a prospective design for which there is no data (Gainsburg, 2013). Thus, it appears that integrating science and engineering may well demand balancing epistemic differences among outwardly similar practices. The more we know about how children engage in engineering practices, the better positioned we are to make informed decisions about how to design learning environments where children can participate in shared science and engineering practices, and to understand the potential trade-offs involved in such pedagogical endeavors.

One key engineering activity is that of *design*—the purposeful, systematic, iterative, and social process by which engineers solve problems (Bucciarelli, 1994; Dym, Agogino, Eris, Frey, & Leifer, 2005; Katehi et al., 2009; Simon, 1996). Design includes, but is not limited to: (a) identifying problems; (b) generating, testing, and analyzing solutions; (c) evaluating alternatives; and (d) optimizing the final solution (Katehi et al., 2009). This focus on design is reflected in most K-12 engineering curricula (Brophy et al., 2008; Katehi et al., 2009). Consistent with the recent emphasis on integrating science and engineering, design is often employed as a means to support children's development of conceptions of disciplinary core ideas in science, such as force, motion, energy, and the behavior of electric circuits (Kolodner et al., 2003; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Mehalik, Doppelt, & Schunn, 2008; Sadler, Coyle, & Schwartz, 2000; Schnittka & Bell, 2011). Yet, little of this research examines the nature of children's engineering practices or how engaging in engineering practices contributes to children developing understandings of interdisciplinary concepts such as cause and effect, structure and function, and the behavior of complex systems.

To study relations between engineering practices and interdisciplinary concepts, we chose to examine how middle school children engaged in the design of pop-up books—an activity known as paper engineering (Benenson & Neujahr, 2009). In particular, we were interested in how learning to participate in forms of engineering practice influenced children's generation of pop-ups, and their perceptions of the structure, behavior, and function of the mechanisms governing pop-ups. Rather than focus on many engineering practices, we chose to focus on children's emerging participation in *reverse engineering* (i.e. the process whereby engineers design and redesign based on deconstructing and examining existing objects), and *troubleshooting* (i.e., the form of problem solving in which engineers use a variety of strategies to evaluate and fix failed products or processes), as emblematic engineering practices.

In addition to our interest in more traditional concerns, such as children's understandings of the mechanisms regulating the behavior of their pop-ups, our interests also extended to aesthetic dimensions of design, for example, style and taste. The inclusion of aesthetic is rooted in a view that design is personal and is regulated by the goals and experiences of the designer (Bucciarelli, 1994) and by the historic interplay between narrative and mechanical function in the world of pop-up design. Therefore, we investigated not only how opportunities to participate in reverse engineering and troubleshooting contributed to children's building and understanding pop-up systems, but also how children's pre-existing *design resources* (i.e., children's tacit understandings of what makes a good pop-up book, children's unique experiences in the world, and children's individual interests) influenced how they built pop-ups.

Finally, because we take design to be more intricate than simply constructing an object based on a collection of abstract relationships governing its form and function, our interests include how children coordinate design resources with knowledge of the structure and function of pop-up systems. Therefore, we set out to investigate if, and to what extent, children drew on design resources and on knowledge of the pop-up system to realize their design goals.

This study was guided by three research questions: (a) What design resources do children bring to paper engineering? (b) How does engaging in the practices of reverse engineering and troubleshooting help children make sense of pop-up mechanisms? and (c) How do children draw on design resources and knowledge of pop-up mechanisms to realize their design goals when building pop-up books? In the next section, we provide a brief introduction to paper engineering.

Paper Engineering

Paper engineering transitions young learners from craft-based activities, where design goals tend to focus on trial-and-error construction, to engineering design, where design goals are subject to more analytic decisions (Hendrix & Eisenberg, 2005). In addition, paper engineering situates young learners in conditions common to different realms of engineering. For example, paper engineering presents an ill-structured environment in which children must make decisions in light of uncertainty about how to build working devices. Each of these decisions can result in situations where children have opportunities to generate and test solutions, analyze and evaluate results, and optimize their devices in relation to an end goal. This environment approximates how engineers deal with uncertainty in their day-to-day work (Jonassen, Strobel, & Lee, 2006).

Other approximations to professional engineering practice include opportunities to prototype and consider trade-offs. For example, prototyping pop-ups can engage students in the exploration of material constraints, such as the rigidity of the paper, simulating how professional engineers sometimes build prototypes to explore material constraints in their day-to-day work (Gebhardt, 2003). In addition, building pop-ups often demands that children consider trading off among structural and functional elements of pop-ups (e.g., children must consider how the attachment site of the pop-up inside the book affects the height and the amount of motion of the pop-up). These types of trade-offs mirror the structural and functional trade-offs professional engineers must make when building objects and devices (Katehi et al., 2009). Finally, like professional engineers, children can work in groups to complete iterative cycles of design and redesign where their prototypes and building techniques are subject to public scrutiny, and where sharing information spurs revision and innovation (Kolodner et al., 2003).

Building Pop-Ups

Children can and do make many different types of pop-ups. Here, we give background on only the types that will allow readers to follow the distinctions made in the results section.

Parallel-fold pop-ups. In order to create a parallel-fold pop-up, the paper engineer tapes an unfolded strip of cardstock (cardstock is more durable than regular paper) into an open bare book (Figure 1, left side). The strip should be taped so that both attachment points (i.e., the *page positions*) are parallel to the center of the book (i.e., the *gutter*) and aligned with each other.

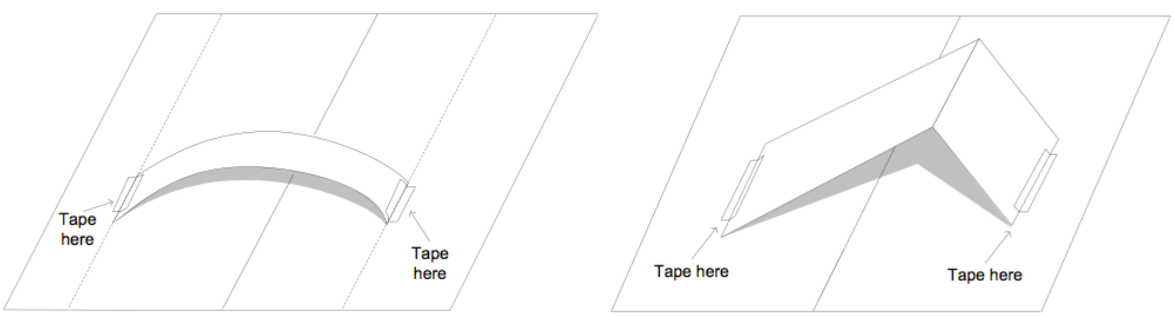

Figure 1. A parallel-fold pop-up (adapted from Benenson & Neujahr, 2009).

After attaching the strip, the paper engineer closes the book. Because the strip is attached to both sides of the book, closing the book causes the strip to push out and fold. The right side of Figure 1 shows how the strip looks when the book is reopened. Attaching the page positions farther from the gutter decreases the pop-up's height while attaching the page positions nearer to the gutter increases the pop-up's height when the book is open. In addition, attaching the page positions equidistant from the gutter results in a symmetrical pop-up and attaching the page positions at different distances from the gutter results in an asymmetrical pop-up. Due to their structure, parallel-fold pop-ups have a distinct "side-to-side" motion.

Angle-fold pop-ups. In order to create an angle-fold pop-up, the paper engineer tapes an unfolded triangle (typically an equilateral or isosceles triangle cut from cardstock) into an open book (Figure 2, left). The triangle is taped so that its apex lies exactly in the gutter and so that its base forms an arch when viewed from the side.

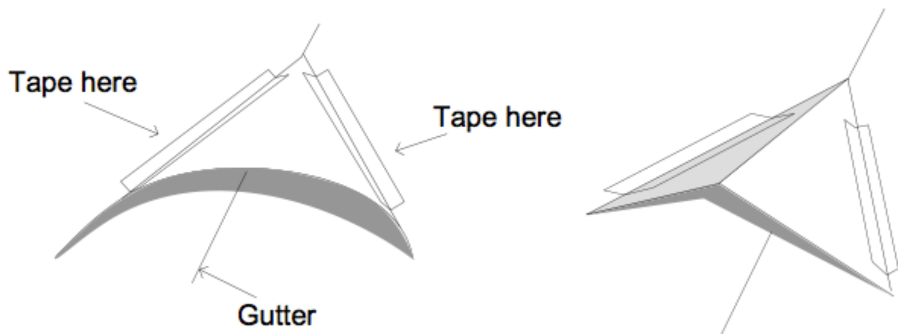

Figure 2. An angle-fold pop-up (adapted from Benenson & Neujahr, 2009).

After attaching the triangle, the paper engineer closes the book. Similar to the parallel fold, because the triangle is attached to both sides of the book, closing the book causes the triangle to push out and fold. The right side of Figure 2 shows how the triangle looks when the book is reopened. Attaching the sides of the triangle at different angles from the gutter changes the height of the pop-up. For example, moving both of the triangle's page positions away from the gutter will prevent the triangle from popping up as high. In addition, symmetric angle-fold pop-ups have page positions with identical angles of attachment to the gutter and asymmetric angle-fold pop-ups have page positions with different angles of attachment to the gutter. Due to their structure, angle-fold pop-ups have a distinct "up and down" motion.

Method

Participants

Participants in the study were 28 children (12 boys and 16 girls) and one teacher from a seventh-grade math class in a suburban school district near a mid-sized southern city. Children ranged in age from 12-14 years old. The class was composed of 61% Hispanic, 25% White, 11% Pacific Islander, and 3% Asian children. Additionally, 57% of children were classified as English language learners (ELL). At the time of the study, 85% of children enrolled at the school qualified for free or reduced lunch. All instruction was led by the classroom teacher, Ms. C (who was shadowed by a student teacher), or by the first author, Mr. R, who acted as a teacher-researcher and who was present in the classroom for the duration of the study.

Instructional Design

Instruction was based on a 10-lesson sequence, each lasting approximately 45 minutes, that we adapted from an existing paper-engineering curriculum focusing on investigations of parallel and angle folds and their composition (Benenson & Neujahr, 2009). We modified the existing curricular sequence by modifying or revising tasks and activities to increase students' opportunities to participate in the practices of reverse engineering and troubleshooting, and to engage them in the activity of authoring their own pop-up book. For example, whereas the original curriculum called for the teacher to lead a single discussion about troubleshooting at the beginning of the second lesson, we made troubleshooting a normative activity throughout instruction by routinely asking children to identify the issues they experienced while building pop-ups. We followed by regularly asking children to share how they solved those issues with the entire class. Moreover, in contrast to the didactic instruction of the original curriculum, we introduced students to parallel and angle folds through reverse engineering commercial pop-up books. Due to time limitations, children completed eight of the ten lessons in the curriculum. However, all children designed and completed their own pop-up books.

In one of the initial lessons, we set up a contrast where half of the class set out to reverse engineer an asymmetric parallel-fold pop-up of a dog whose tail moved back and forth from left to right upon opening and closing the book (Figure 3, left side), and half of the class set out to reverse engineer a symmetric angle-fold pop-up of a bird whose beak moved up and down upon opening and closing the book (Figure 3, right side). The reverse engineering design challenge entailed children removing the pop-up from the commercial book (i.e., literally tearing it out of the book) and reattaching it into a transparent book so that it worked correctly.

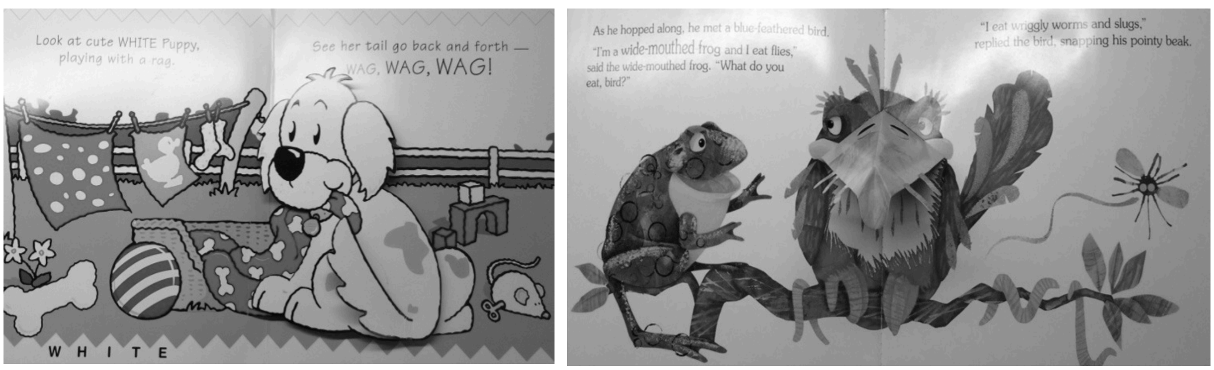

Figure 3. A parallel-fold dog pop-up (Lee & Repchuk, 1998) and an angle-fold beak pop-up (Faulkner, 1996) from two commercial books.

By engaging children in this activity, we intended to initiate thinking about (a) the differences in the motion of parallel and angle folds when the book was opened and closed, and (b) the practical means of attaching a pop-up to the pages of a book. During collective discussion, we highlighted the difference in apparent motion and related these differences to the kind of fold. This episode of reverse engineering served as a touchstone as students later aimed to design their own pop-ups. For example, when children investigated the motion of symmetric and asymmetric parallel folds, Ms. C asked them to compare the structure and motion of those parallel folds to the structure and motion of the parallel-fold dog pop-up.

Finally, we attempted to craft a learning ecology (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) that would simultaneously support children participating in reverse engineering and troubleshooting and developing knowledge of pop-up mechanisms. Therefore, when planning instruction, we carefully considered how to orchestrate (a) tasks (i.e., what we asked children to do), (b) material means (i.e., the technologies we made available to children to mediate learning), (c) activity structures (i.e., the ways in which we asked children to participate, such as discussions where the whole-group considered different solutions to design challenges or individuals demonstrated the workings of a particular design to sustain a claim made about it), and (d) inscriptions (i.e., the text and drawings we asked children to write and record) (Lehrer, 2009). In the following sections, we briefly explain the role each played in the instruction.

Tasks. We attempted to ground curricular tasks in the production of effects occurring in commercially available pop-up books. Hence, throughout instruction, we made a variety of commercial pop-up books available for children to examine. We reasoned that providing children with opportunities to inspect commercial pop-up books would (a) familiarize them with the world of paper engineering, (b) position them to imagine themselves as aspiring paper engineers, and (c) encourage them to explore links between the books' structural and functional features. Furthermore, we asked children to make observations about the literary aspects of the books by identifying elements of the story such as the introduction, climax, main characters, and setting. The purpose was to alert children to the key characteristics of pop-up book stories so that they could draw on similar characteristics of story when authoring their own books.

We also organized instruction around *design challenges*—tasks in which children constructed pop-ups with the goal of achieving a desired effect. Design challenges were ill-structured (i.e., there were several ways to successfully solve each design challenge) and highlighted issues that children often face as they build pop-up books. For example, children were challenged to design and build a pop-up that popped up when the book was open. Although all children were able to build a pop-up that popped up when the book was open, most children found that when they closed their books, the pop-up protruded beyond the pages of the book. This design challenge problematized the relationship between how a pop-up rises off the page when the book is open yet stays inside the book when it is closed, encouraging children to troubleshoot the problem. Hence, design challenges exposed children to the concept of iteratively refining their pop-ups based on failure. Other examples of design challenges that we posed included asking children to build pop-ups that popped up as high as possible, popped up on one side of the book or the other, or popped up with a greater or lesser degree of motion.

Material means. We supplied small groups of children with a “class set” consisting of six different commercial pop-up books selected based on (a) attributes of the story (i.e., the books demonstrated a range of settings and a range of themes), (b) the types of folds present in the various pop-ups (i.e., some books used mostly parallel folds and others used mostly angle folds), (c) the degree of complexity of the folds (i.e., some books were simple and others were more complex, consisting of more intricate folds such as multiple folds connected in series), and (d) visual components (i.e., some books were plainly illustrated and others were ornately illustrated). Our goal was to supply children with a variety of books providing them with a wide array of examples that they could consider as models for authoring their own pop-up books.

We also provided children with materials that made engaging in design challenges accessible. For example, we provided transparent books for children’s initial pop-up design. Transparent books allowed children to move pop-ups into and out of the book easily (i.e., the tape did not tear the pages like it sometimes can in paper books) and allowed children to inspect the full range of motion produced by opening or closing the pages. We conjectured that making this previously invisible view of a pop-up visible would help children make connections between structural and functional aspects of pop-ups, such as the relationship between page position location and the degree of motion. In addition, we adopted a vertical line grid in the transparent book. These lines ran parallel to the gutter and were spaced one centimeter apart. We reasoned that children might use this grid as a resource for reasoning about the relationship between pop-up attachment and pop-up motion. Finally, we also sought to help children visualize the types of motion in different pop-ups (e.g., side-to-side, vertical, and rotational) by asking them to attach Post-it® note flags to the pop-ups they inspected and made.

Lastly, we provided materials for children to build prototype books and final books. Building prototype pop-up books was an intermediary step between building transparent books and building final books. Children constructed prototypes using a single sheet of cardstock as the book. Hence, prototype pop-ups resembled pop-up greeting cards. After constructing parallel-fold and angle-fold prototypes, children authored their final pop-ups in "chunky" Bare Books. Chunky Bare Books were blank books made from rigid cardboard with a glossy finish on the pages. Each book had ten pages, which meant that each book could accommodate five pop-ups, a number manageable for children to build over the course of instruction, and a sufficient number to accommodate telling a story.

Activity structures. Classroom activity was dominated by cycles of small-group work followed by whole-group discussion. Children typically began working in small groups to solve a design challenge. As children worked, teachers visited the different groups and asked questions meant to elicit information about how children solved the challenge. For example, Mr. R often asked children if they had issues attaching a pop-up into a transparent book. When a child reported experiencing an issue, Mr. R probed how he or she troubleshot the issue.

After children worked in small groups to solve a design challenge, teachers orchestrated whole-group discussions as venues for children to report how they solved the challenge. During these discussions, children shared examples and discussed the issues they experienced as they solved design challenges. In some instances, teachers encouraged children to explain their ideas using gestures (this was particularly common when children were discussing how particular pop-ups moved). Throughout whole-group discussions, teachers regularly asked children to share drawings, findings, and artifacts with the class using the classroom projector. This recurring activity structure was meant to showcase individual children's artifacts to other members of the class and to help children build on one another's ideas about pop-up structure and function.

Teachers managed children's participation by circulating around the classroom as children solved design challenges. Thus, during whole-group discussion, teachers were in a position to select and highlight particularly interesting or provocative solutions. Moreover, teachers frequently juxtaposed similar (and different) design solutions to encourage whole-group discussion. Finally, during both whole-group and small-group activity, teachers made links between children's designed artifacts and the commercial pop-up books in the class set.

Inscriptions. Throughout instruction, children documented their progress in workbooks called designer learning logs. Children used designer learning logs to record (a) issues they experienced as they attempted to solve design challenges, (b) ways they troubleshot to solve those issues, (c) representations showing and explaining pop-up structure and pop-up motion, and (d) any information they learned from participating in design challenges. Designer learning logs became important resources for teachers to consider how children were thinking about the solutions to design challenges. Additionally, children frequently inspected their designer learning logs at the start of each lesson to review what they had done in previous lessons.

Children also completed story and page "maps" designed to scaffold their attempts at writing stories and at laying out the pages of the book. We conjectured that story and page maps would help children gain traction planning their pop-up books. In particular, we designed story maps to help children begin writing their stories. Story maps had entries for title, setting, and characters, where children could brainstorm these elements of their story. Likewise, we designed page maps to help children begin planning how each page of their book would look. Page maps had space for children to sketch drawings and to plan physical relationships on each page.

As children filled out their story and page maps, we encouraged them to draw inspiration from the class set of commercial books. We also encouraged children to bring in literature they enjoyed, and perhaps read at home, on which to model their books. Finally, with the librarian's guidance, we checked out a wide selection of popular seventh-grade literature from the school library (e.g., poetry, scary stories, graphic novels, and comic books) and encouraged children to examine as many examples as possible as they planned their own pop-up books.

Data Collection

We used a variety of data sources to help answer our research questions. These data sources included (a) pre-instruction surveys, (b) daily small-group and whole-group observations, (c) individual interviews with children prior to and after instruction, and (d) a range of student-created artifacts. We review these data sources in the four subsections below.

Pre-instruction surveys. Prior to instruction, we administered surveys meant to collect baseline information about what children (a) knew about pop-up books, and (b) valued about pop-up books. The survey included questions such as: Do you like pop-up books? How often do you read pop-up books? What makes a good pop-up book? and, Do you ever read comic books or graphic novels, and if so, which ones? Twenty-five out of the 28 children in the class completed the pre-instruction surveys.

Daily observations. For each day of instruction, we video recorded both small-group and whole-group classroom activity. Children were placed into groups based on who Ms. C believed would work well together, and based on mixed mathematical ability. We used one stationary video camera to record the talk and action of a single group of four children, the focus group. Over the course of 15 days of instruction, we recorded approximately 11 hours of small-group activity. We also recorded the same amount of whole-group activity using a second camera, operated by a videographer, which followed the classroom conversation. This camera moved frequently between teachers, who orchestrated the conversation, and children, who shared the pop-ups they built and explained how they solved design challenges.

Individual interviews. Prior to instruction, we interviewed 10 children to determine what they noticed about pop-ups. We selected children based on Ms. C's belief that they would willingly share their thoughts with us, and because they represented a range of mathematical ability based on the results of the annual statewide mathematics test. During these interviews, we presented children with five paired comparisons of commercial pop-ups illustrating a range of symmetric and asymmetric parallel and angle folds. For each pop-up, we asked children to explain what they noticed, as well as to identify how the pop-ups were similar or different from one another. These interviews ranged from 9 to 17 minutes. On average, each interview lasted about 13 minutes. Table 1 details the pop-ups we used in each comparison and explains which attributes each comparison highlighted.

Table 1

Pre-Instruction Paired Comparison Interview

Comparison	Book A	Book B	What the comparison highlighted
1	*Let's Make It Pop-Up* Symmetric parallel fold. (Butterfly)	*Snappy Little Colors* Asymmetric parallel fold. (Dog)	Similarities and differences between the page positions and the motion of symmetric and asymmetric parallel-fold pop-ups.
2	*Let's Make It Pop-Up* Symmetric parallel fold. Medium height. Medium motion. (Box)	*Wide-Mouthed Frog* Symmetric angle fold. Medium height. Medium motion. (Bird)	Similarities and differences between page positions, directional motion, range of motion, and height of symmetric parallel-fold and symmetric angle-fold pop-ups.
3	*Wide-Mouthed Frog* Two symmetric angle folds. High height. Low motion. (Alligator)	*Giant Pop-Out Shapes* Two symmetric angle folds. Low height. High motion. (Heart)	Similarities and differences between the page positions and the range of motion of angle-fold pop-ups opening to different heights.
4	*How Many Bugs in a Box?* Three symmetric parallel folds (Butterflies)	*Snow Bugs* Three asymmetric angle folds (Snowballs)	Similarities and differences between the page positions and the directional motion of multiple symmetric and asymmetric parallel and angle folds on the same page.
5	*Snappy Little Colors* Two angle folds connected in series. (Crab)	*Snappy Little Colors* One angle and one parallel fold connected in parallel. (Mole)	Similarities and difference between the page positions and the directional motion of combinations of parallel and angle folds on the same page.

Note. Each paired comparison highlighted similarities and differences between structural and functional attributes of parallel and angle folds such as page position, direction of motion, range of motion, and height of the pop-up off the page.

Additionally, after children authored their books, we interviewed 13 children about the pop-ups they built. This group consisted of nine children interviewed prior to instruction and four additional children selected by Mr. R based on their willingness to share their project experiences with their classmates and with teachers. One child who we interviewed prior to instruction declined to be interviewed after instruction. For each pop-up, we asked children questions such as: How did you decide to make that pop-up? How does your pop-up help tell your story? Did you experience any issues building this pop-up? Did you use troubleshooting to fix any issues? and, Did you use reverse engineering to help build this pop-up? These interviews ranged from 7 to 28 minutes. On average, each interview lasted about 17 minutes.

Student-created artifacts. Children authored and built a number of artifacts over the course of instruction. For example, children authored the content of their designer learning logs and page and story maps. Also, children built prototype pop-up books and final pop-up books. We collected, scanned, or photographed all of the artifacts children created during instruction. Notably, rather than collecting children's final books, we took pictures of each child's book. This allowed children to take their books home, which they were excited to do.

Analysis

To answer our first research question, (i.e., What design resources do children bring to paper engineering?), we began by examining children's pre-instruction surveys to determine which attributes of pop-ups children recognized and valued. Next, we inspected children's pre-instruction interviews to discover what children noticed about commercial pop-ups. We proceeded by watching each interview (n = 9) and developing a coding scheme meant to characterize trends in what children noticed when inspecting different commercial pop-ups. We then re-watched each interview and applied our coding scheme to find the relative frequencies of what children noticed. Finally, we looked across children's story and page maps to identify themes that emerged as children planned how to author their own pop-up books.

To answer our second research question, (i.e., How does engaging in the practices of reverse engineering and troubleshooting help children make sense of pop-up mechanisms?), we first developed content logs of the entire body of whole-group and small-group classroom activity. In addition, we also developed outlines of what children reported in their designer learning logs and in their story and page maps. We then condensed these content logs and outlines into instructional summaries, tracing children's activity over the course of each lesson.

Next, we reviewed the instructional summaries we created in weekly research meetings. During these meetings, we conducted group video noticings (Jordan & Henderson, 1997) during which we examined and discussed instructional episodes and developed memos to trace instances in which children engaged in or referred to reverse engineering and troubleshooting. Throughout this iterative process, we periodically returned to the data to refine our observations. In this paper, we report on instances spanning the initial reverse engineering design challenge and extending into later lessons where children built parallel folds and angle folds.

To answer our third research question, (i.e., How do children draw on design resources and knowledge of the pop-up system to realize their design goals when building pop-up books?), we examined children's post-instruction interviews. We began by transcribing the 13 post-interviews. Next, we searched for and recorded instances where children coordinated talk about design resources with knowledge of pop-up structure and function to reach a design goal. Lastly, we collapsed children's responses into two broad categories, using folds in the service of telling stories, and using knowledge of pop-up structures to solve aesthetic problems.

Results

We present the results in three parts. First, we describe the design resources children brought to the paper engineering activity. Second, we explain how engaging in the practices of reverse engineering and troubleshooting helped children reason about pop-up mechanisms. Third, we illustrate with selected cases how children drew on design resources as well as on knowledge of the pop-up system to realize their design goals when building their pop-up books. To illustrate our findings, we draw on examples of children's writing, talk, and artifacts.

Part I: Children's Pre-Existing Design Resources

Aesthetics and story emerged as two of the most prominent design resources children brought to the paper engineering activity. In the subsections below, we define each of these terms and describe how they emerged as prominent design resources.

Aesthetics as a design resource. We use the term aesthetics to encompass the visual, artistic, and stylistic elements of a pop-up book. Hence, aesthetics include how pop-ups look as well as how pop-ups move. Here we outline how children's responses to pre-instruction surveys and pre-instruction interviews indicated aesthetics as a design resource.

Pre-instruction surveys. Pre-instruction survey responses revealed that most children (a) had knowledge of pop-up books, (b) considered pop-up books fun to read, and (c) were excited to make their own pop-up books. Additionally, over 50% of children surveyed indicated the importance of aesthetics when judging whether or not a pop-up book was "good." For example, when asked what made a good pop-up book, Jorge responded, "usually what gets my attention on a pop-up book [are] colorful pop-ups. Usually I get pop-ups with more colors." Similarly, Violet reported that good pop-ups were "very colorful and very exciting," and that they had "lots of details and lots of pop-outs." Children also reported that attributes such as creativity and complexity made some pop-ups better than others. For example, Lily explained that good pop-ups were “more sophisticated and more complex” than other pop-ups. Likewise, David noted that good pop-ups were “interesting, unique, and creative.”

It should be noted that children’s survey responses also indicated that they were skeptical of their own abilities to make quality pop-ups. For example, when asked if they thought they would be able to make good pop-ups, many children reported thinking that they would not be able to make good pop-ups because they were not good artists. The metric for being considered a good artist seemed to be whether or not a child could draw well.

Pre-instruction interviews. Children most frequently noticed objects and colors when they inspected pairs of pop-ups during the pre-instruction interview. For example, when asked what he noticed about the first pop-up in the first paired comparison, David remarked, “it’s a butterfly, and it’s colorful.” Similarly, when asked what she noticed about the first pop-up in the fifth paired comparison, Emani exclaimed, “it’s a big orange crab that has a smile on it.” All children interviewed reported noticing objects or colors in two or more of the paired comparisons and 55% reported noticing objects and colors in all five paired comparisons. Overall, 44% of all the utterances children made across comparisons indicated that they noticed objects and colors.

In addition to noticing objects and colors, 78% of children also reported noticing differences in pop-up size and complexity. For example, when asked what she noticed about the second pop-up in the third paired comparison, Carissa answered, “it’s a heart, and it’s red, and it’s big when you open it.” Like Carissa, Emani also noticed a difference in pop-up size when she observed the first pop-up in the third paired comparison was “bigger, longer, [and] it’s green.” Rosalie, on the other hand, noticed a difference in pop-up complexity when she reported that the first pop-up in the third paired comparison had “two parts—the bottom and the top of the mouth." Overall, just over 11% of the utterances children made across pop-up comparisons were remarks indicating that they noticed differences in pop-up size and complexity.

Sixty-six percent of children reported noticing that pop-ups had directional motion. For example, when inspecting the second pop-up in the first paired comparison, Rosalie explained, "the tail moves different. It's at the right and then it goes to the left." Likewise, Kara pointed out directional motion when inspecting the second pop-up in the third paired comparison. Kara noted, "when the mouth moves to the center, the bottom of it goes up. This part right there goes up to meet the mouth." Children were slightly more apt to notice attributes of pop-up motion than they were to notice differences in pop-up size and complexity. For example, 16% of children's utterances across pop-up comparisons were related to directional motion.

In addition to noticing directional motion, 66% of children also noticed the degree to which pop-ups extended out of the book. For example, after inspecting the pop-ups in the first paired comparison, Kiyara explained, "once you open the book, they both pop out and stand out in 3-D." Similarly, when inspecting the pop-ups in the third paired comparison, Jeff explained, "this one actually pops up towards you, and this one's just flat." After inspecting the same pair of pop-ups, Carissa invoked the concept of expansion to explain the degree to which the two pop-ups extended out of the book. Carissa reported, "they both expand to be bigger…this one pops out when you expand it and this one stays flat." Thus, children sometimes identified spatial characteristics of pop-ups and described the "degree of pop" in relation to space. Overall, utterances related to the degree of pop accounted for just over 18% of children's noticings.

Lastly, 66% of children reported noticing aspects of pop-up structure when examining commercial pop-ups, but they generally did not coordinate structure to function. That is, children did not explain how a specific fold produced a particular motion. For example, after examining the pop-ups in the fifth paired comparison, Rosalie explained, "and I see it [the second pop-up] has more structure to it than this one. It has like—it takes more things to make it go up." Here, Rosalie tacitly related pop-up structure to pop-up function. In her interview, Kara explicitly identified the relationship between a pop-up's structure and its function when she speculated why the second pop-up in the first paired comparison worked the way it did. Kara noted, "when you close it and open it, the tail moves. And there's probably a little bit of paper behind him to make it stand out a little more." In general, examples of children linking pop-up structure to pop-up function were rare, accounting for fewer than ten percent of children's total utterances.

Story as a design resource. We use the term story to stand in for the range of literary elements present in a pop-up book. Hence, story includes literary elements such as main ideas, main characters, and themes. In this section, we explain how story emerged as a design resource in children's pre-instruction surveys and in children's story and page maps.

Pre-instruction surveys. Children's pre-instruction surveys indicated that story contributed to making some pop-up books better than others. This was evinced by approximately one third of children reporting that a good story was an important aspect of a pop-up book. For example, Alvin explained, "a good pop-up is made by a fictional story, that everyone likes." Similarly, Cedric explained that a "a good pop-up has to have a good story and interesting characters." Additionally, several children reported that a good story connected to the book's aesthetic components. For example, Dana reported, "I think what makes a good pop-up book is an interesting story that goes along with the pictures." Thus, overall, children entered the paper engineering activity with a sense that story contributed to what makes a pop-up book good.

Children's story and page maps. Children drew from eclectic sources when planning how to write their own pop-up book stories. For example, (32%) of children used the commercial books in the class set as inspiration for writing their own books. One child, Kara, modeled her book on *The Wide-Mouthed Frog*, a book in which the main character, a frog, chatted with different animals on each page. Kara adopted this storyline and altered it by recasting the main character as her dog, Chulo the Chihuahua, who traveled around a farmyard chatting with various farm animals. For a summary of the major sources children drew from when authoring books, see the Appendix. It should be noted that because we classified children's stories into more than one category, the percentages we report in this section sum to more than one hundred.

Children also used the concept of a central theme found in a number of commercial books to help them organize the individual pages of their books and to manage the complexity of writing their stories. Central themes were broad topics that pervaded commercial books and that linked one page to the next. For example, commercial books often used topics such as bugs and colors as central themes. One student, Abby, adopted animals as a central theme in her book. On each page, Abby planned to make a pop-up of a different animal in its native habitat. Choosing animals as a central theme allowed Abby to coherently connect the content of each page of her book without becoming overwhelmed by the task of authoring a longer story.

Children also drew from graphic novels and related books in their school's library to help plan how to write their own pop-up books. Eighteen percent of children based their stories on a library book. For instance, Ariel based his book on a graphic novel about the sinking of the Titanic. Interestingly, Ariel also planned to include images of characters from the movie *Titanic* in his book. In this instance, Ariel drew on multiple accounts of the same historical event, and from multiple forms of media, to plan the pages of his book. At other times, drawing from library books meant that children copied directly from a library book into their own book. For example, several children copied poems verbatim from Shel Silverstein's *Where the Sidewalk Ends*. In these instances, children appropriated the text of a book because they found it interesting or because it helped them manage the complexity of authoring their own pop-up.

Twenty-nine percent of children based their books on events stemming from their own lives. For instance, one child, Janice, drafted a story based on her experiences of being bullied for being small, smart, and for wanting to become a dentist. The school had championed an anti-bullying campaign all year, and this was a campaign in which Janice was active. Other examples of real-life accounts children planned to write about included attending birthday parties and participating in sporting events. In addition to planning to write about their own lives, children often included their friends as characters in their books. For example, Gwen, who had recently tried out for the cheerleading team at the local high school, planned one page of her book to show her cheering at one of her friend's basketball games. Hence, a number of children's stories were rooted in personal experiences with friends and family members.

Eleven percent of children were inspired by stories about Internet characters. For example, Jorge planned to write about how Nyan Cat (a chimeric pop-tart cat who leaves a rainbow trail in his wake wherever he flies) saved the world by thwarting an evil plot by Tac Nyan (a chimeric waffle cat—and Nyan Cat's nemesis). (See the left side of Figure 4 for an image of Nyan Cat.) Similarly, Jeff planned to write about Mr. Toast's (a genial piece of toast) former life as a circus performer, and David planned to write about a mash up of My Little Pony® characters fighting in "the war of doom." (See the right side of Figure 4 for an image of a warring My Little Pony® character.) Planning to write about Internet characters allowed children to generate back-stories for characters they found interesting. Also, it allowed children to extend the storyline of an established character. We consider this phenomenon to be an example of fan fiction, a genre of writing in which fans author fictional offshoots of a character's storyline by meshing their own ideas with those of the original authors.

Finally, one third of the children in the class planned to write stories that were unrelated to a commercial pop-up book, a library book, a real-life experience, or to an Internet character. For example, Alvin planned to write his book about a wizard and his magical menagerie, while Everett planned to write his book about UFOs and alien abductions.

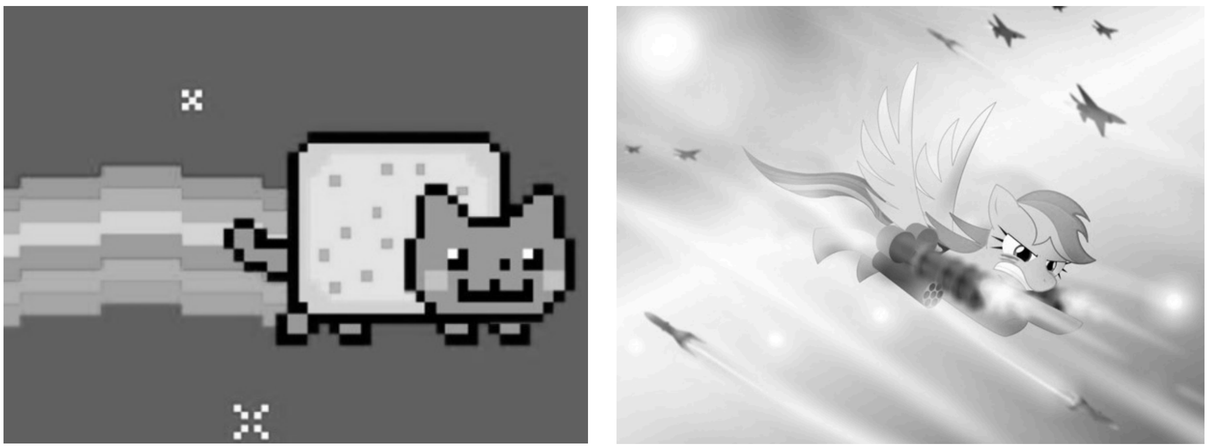

Figure 4. Some children planned to write about popular Internet characters. On the left side is Nyan Cat. Image retrieved from http://iheartnintendo.com. On the right side is a warring My Little Pony® character. Image retrieved from http://www.fobequestria.com.

Summary: Children's design resources. To summarize, our analysis of children's pre-instruction surveys, pre-instruction interviews, and page and story maps revealed that children considered aesthetic components such as, objects, colors, size, complexity, degree of pop, and type of motion as important aspects of pop-up books. Moreover, children also considered it important to tell expressive stories, often modeled on their own life experiences and after culturally available media such as commercial pop-ups, library books, and Internet characters. In contrast to this comparatively rich repertoire, few students appeared to consider elements of mechanisms, such as how the motion of the pop-up was related to the type of fold, or how page positions affected pop-up height. We aimed to develop children's sensitivity to these aspects of paper engineering by supporting instruction, as we explain in the next section.

Part II: Using Reverse Engineering and Troubleshooting to Reason About Pop-Up Systems

As described previously, we explicitly supported reverse engineering and troubleshooting throughout instruction as we considered these to be emblematic engineering practices. In the following two sections, we explain the role that reverse engineering and troubleshooting played in helping children reason about pop-up structure and pop-up function.

Reasoning about pop-up structure and function through reverse engineering. During the initial reverse engineering design challenge, children reported recognizing structural aspects of the pop-up system. For example, when attempting to reverse engineer the beak pop-up (this is the angle-fold pop-up pictured on the right side of Figure 3) in a transparent book, a focus group initially attached it at too steep an angle to the gutter, preventing the book from closing correctly. That is, when they closed the book, children found that the beak did not fold up completely to fit into the book. After identifying the problem, the children repositioned the beak so that it was attached in a different orientation (i.e., at less of an angle to the gutter), allowing the book to close. The transcript of this episode appears in the excerpt below.

Mr. R: Did you have any issues?

Rosalie: Mario placed it wrong and Kara fixed it.

Mario: It was too inside—like too close to the gutter.

Mr. R: OK. What was too close to the gutter?

Mario: The folds [page positions] were too close to the gutter.

Mr. R: Point to them.

Kara: This part right here [touches the beak's page positions].

Mr. R: That was too close? Show me how they were too close to the gutter.

Kara: It was like…instead of…[removes the beak from the transparent book and repositions it to decrease the angle of attachment to the gutter] it was like that.

Mr. R: So what was the problem with that?

Mario: It wouldn't fold.

Mr. R: Oh, it wouldn't close correctly?

Kara: And when I placed them [the page positions] farther apart, it closed correctly.

Mr. R: Oh, OK. So what—is there anything that you learned?

Rosalie: It has to be a certain position—it has to be at a certain position.

Kara: You have to place it correctly.

In this conversation, Mario initially reported that because the beak's page positions were too close to the gutter, it prevented the transparent book from closing correctly. When Mr. R asked why this was problematic, Mario explained that the book "wouldn't fold." Kara explained fixing this issue by adjusting the beak's page positions so that they were at a greater angle to the gutter. Reasoning about fixing this issue led Rosalie and Kara to recognize that the beak needed to be attached at a certain position on the page and in a particular orientation to the gutter.

Later, when asked to share what he learned from the activity in the whole group discussion, Mario explained that for the beak to work correctly, the page positions needed to be attached in "specific locations." Likewise, when responding to the prompt *What did you learn?* in his designer learning log, Cedric explained, "To reverse engineer, you need to know where to attach the pop-up." Thus, reverse engineering seemed to help children recognize features (e.g., attachment points) that determined if a pop-up functioned as anticipated. This form of knowledge was based in performance and did not address concepts such as angle and its measure.

Children also experienced other structure-function relationships during the reverse engineering design challenge. For example, some children recognized that for a pop-up to work exactly as it did in the commercial book, it had to be attached to both pages of the book, and it had to span the gutter. In the excerpt below, Mario explained discovering this relationship after attaching the beak to one side of the transparent book and observing that it did not work. Italics denote emphasis added by the researchers.

Mr. R: Mario, you were saying you had it over here [attached to one side of the book] and it didn't work—right? Why not? Why did it not work?

Mario: Because nothing was like *pulling* it apart to make it pop-out.

Rosalie: It just stayed flat.

Mr. R: It just stayed flat? And tell me more about this—so you're saying nothing was pulling it apart?

Mario: Yeah. Like since this one [using another book as an example], whenever you open it, this one's like *stretching* it out and it'll make it pop-out. And whenever that one was on the side, it was just staying there. Nothing was happening.

In this episode, Mario reported noticing that the beak did not function when attached to one page in the transparent book. Mario attributed the lack of function to the absence of a mechanism responsible for pulling the beak apart and for making it pop-up. Essentially, Mario discovered the most basic feature for making any pop-up work, connecting the pop-up to both pages across the gutter allows a force to be transmitted across the book so that when the book is opened, the pop-up rises off the page. Without this basic feature, pop-ups do not function. Again, students did not invoke concepts such as force but instead referred to a tactile sense of pulling.

After each group successfully reverse engineered the commercial pop-up into their transparent book, children explored how their reverse-engineered pop-ups moved by attaching Post-it® note flags to them and then by opening and closing the transparent book. This activity highlighted distinct types of motion. For example, Alvin reported noticing that the dog pop-up (this is the parallel-fold pop-up pictured on the left side of Figure 3) moved from “side-to-side,” while Kara reported that the beak pop-up “started from the left then moved down towards the bottom right.” Thus, attaching flags appeared to help children visualize how parallel folds moved laterally across the gutter and how angle folds moved in vertically oriented arcs (e.g., from top left to bottom right). Although students typically discriminated these motions before instruction, reverse engineering helped them establish relations between motion and types of folds.

Children depicted several types of motion when recording how their reverse engineered pop-ups moved in their designer learning logs. First, children showed directional motion. For example, children illustrated the side-to-side motion of the dog pop-up as well as the up and down motion of the beak pop-up. Second, children showed the rotational motion of the beak. For example, Mario wrote that the beak “rotated,” while Abby explained that the beak “moves from the end of the page to the middle along with the bird” (see Figure 5).

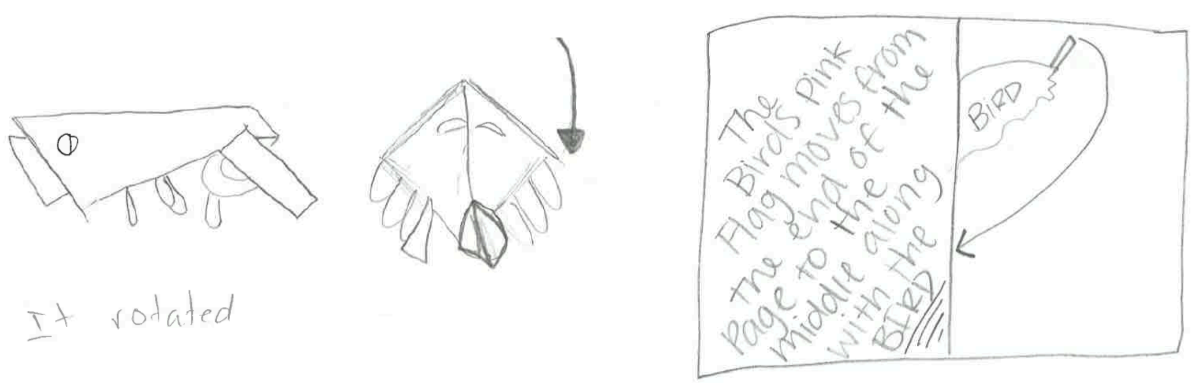

Figure 5. Two different depictions of the angle-fold beak pop-up’s motion.

Some children also depicted the 3-dimensional nature of pop-up motion. For example, Manuel drew and explained that the beak was flat when the book was closed, but popped up when the book was opened. Hence, inscribing motion allowed children opportunities to reflect about attributes of pop-up motion that were related to the types of motion children initially reported noticing when examining pop-up books during the pre-instruction interview.

Throughout instruction, Mr. R and Ms. C routinely asked children to make connections between ongoing design challenges and this episode of reverse engineering. For example, on day six of instruction, after several children shared their diagrams of how parallel folds moved with the class, Mr. R asked if anyone recalled the reverse engineering design challenge when examining how their parallel-fold pop-ups moved. Mr. R's question prompted Janice to draw a connection between the parallel-fold design challenge and the reverse engineering design challenge where she and her group reverse engineered the dog pop-up. Her observations prompted a discussion about the similarities and differences of the two pop-ups the class reverse engineered. During this discussion, Ms. C displayed both the dog pop-up and the beak pop-up.

Ms. C: Can I see the dog again? What do you notice about its page positions?

Student: It has three.

Ms. C: OK. What about them though? Let's look at the bird's page positions. What do you notice about the bird page positions?

Leah: It's angled.

Ms. C: What do you mean it's angled?

Leah: The page positions are angled instead of parallel.

Ms. C: OK. So they're going to the side. Are these [referring to the dog pop-ups page positions] parallel? Or are these angled?

Student: Parallel.

In this instance, Ms. C juxtaposed the dog and beak pop-ups and encouraged children to examine the structural features of each. Leah shared with the class that there were differences between the two pop-ups when she pointed out that the two pop-ups had different page positions. This example demonstrates how teachers promoted children observing differences in pop-up structure and making connections to the reverse engineering design challenge.

Additionally, several times over the course of instruction, children extemporaneously referenced the reverse engineering design challenge when describing how their pop-ups functioned. For example, on day nine of instruction, Mr. R noticed that while attempting to build an angle fold that popped up as high as possible, one group began re-examining their reverse-engineered beak pop-up. When the whole group came back together to share about the challenge, Mr. R asked one member, Violet, to share if she noticed any similarities or differences between the angle fold and the beak they had reverse engineered. Violet explained that both the beak and the angle fold moved down when she opened the book. Here, Violet and her group made a connection between the beak's motion and the motion of the angle fold under construction. This instance demonstrated how children connected aspects of the reverse engineering design challenge to the pop-ups they built in later design challenges without teacher prompting.

Reasoning about pop-up structure and function through troubleshooting. Children reported troubleshooting to solve the structural and functional issues they experienced in the initial reverse engineering design challenge. For instance, when attaching the reverse-engineered pop-up into the transparent book, many children found it difficult to replicate the way the pop-up had moved in the commercial book. Children reported troubleshooting to fix this issue by changing the position of the pop-up in the transparent book to where it would have been in the commercial book. For example, Dana explained that it was helpful to “put the pop-up in the same place [in the transparent book] as in the commercial book.” Likewise, Kara explained, “In the [commercial] book, we saw that the pop-up was attached to both pages and that it was placed in the center of the book. So we did the same thing [in the transparent book] and it popped up just like in the [commercial] book.” Hence, troubleshooting where to attach the reverse engineered pop-up helped children identify basic relationships governing how all pop-ups function (i.e., pop-ups must span the gutter and attach to each page).

Children continued to troubleshoot functional issues they encountered as they began building pop-ups in subsequent design challenges. For example, on day four of instruction, Mr. R challenged the class to build parallel folds by attaching cardstock strips into transparent books so that the strip popped up when the book was open. Although most children could make the strip pop up when the book was open, when the book was closed, the strip often protruded out of the book. For instance, Gwen reported that the strip “wouldn’t stay inside [the book].” To fix this issue, Gwen “put it [the strip] closer to the gutter.” Gwen’s response was representative of many of the children in class. Children reported troubleshooting by adjusting the strip’s page positions so that it would fit into the book. Children eventually established a heuristic for building parallel-fold pop-ups that would fit inside of the book—attach the page positions nearer to the gutter.

Children also reported troubleshooting issues when solving design challenges where they built pop-ups that functioned in particular ways. For example, on day five of instruction, Mr. R challenged the class to build parallel-fold pop-ups by attaching cardstock strips into transparent books so that the strips popped up as high as possible. Much of the whole-group discussion following this design challenge revolved around Adnan’s pop-up. When Adnan displayed his pop-up to the class, he explained finding that the nearer he attached his page positions to the gutter, the higher his pop-up came off the page, and the farther he attached his page positions from the gutter, the less his pop-up came off the page (see transcript and Figure 6 below).

Adnan: I put mine [the strip] closer to the middle [the gutter] ‘cause it makes it taller.

Ms. C: What did you put closer to the middle?

Adnan: The page positions.

Ms. C: So you put your page positions close. OK. Why did that work?

Adnan: Because I put it [the page positions] farther and it [the strip] was flat.

Ms. C: Can you show with your hands what you did at first? What do you mean by farther?

Adnan: I moved these [the page positions] farther over [gestures to the left and right with fingers] and it was flat. So I put them together and it made it stand up.

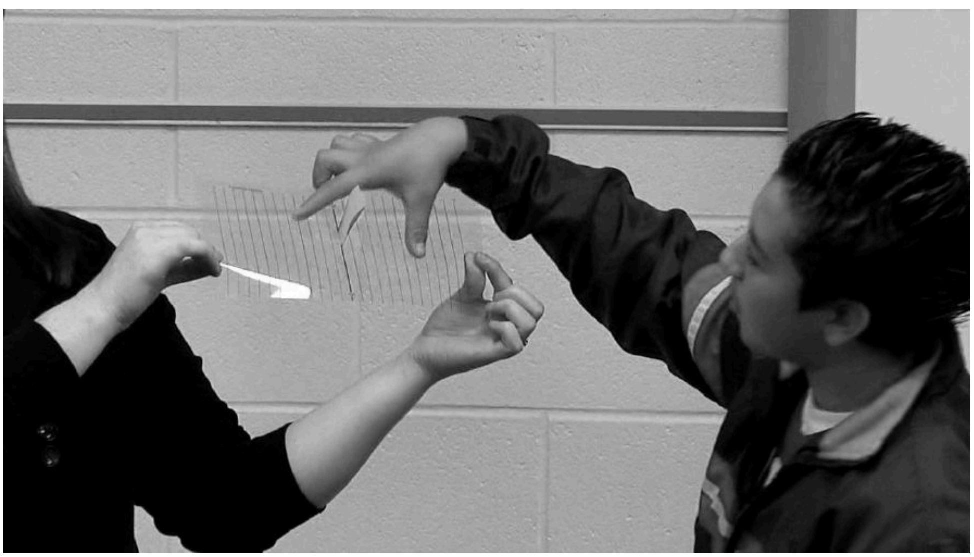

Figure 6: Adnan’s attached his parallel-fold pop-up near the gutter. Using words and gestures, he explained that moving the page positions away from the gutter caused the pop-up to become flat.

In this instance, Adnan initially encountered an issue; because he attached the page positions at a greater distance from the gutter, his parallel-fold pop-up was flat. He investigated this failure by changing the strip’s page positions so that they were nearer to the gutter, causing the pop-up to rise higher off the page. Other children also reported discovering that the distance of the page positions from the gutter influenced the height of the pop-up. For example, Violet reported, “when it [the strip] is closer to the gutter, it sticks out more but when it’s further away it [the strip] just wants to be flat.” Similarly, Ariel explained, “so it [the strip] can be tall, you have to tape it closer to the gutter. If the page position is closer to the gutter then the pop-up will stand taller.” Thus, troubleshooting the location of the strip’s page positions helped children to establish a structure-function relationship for parallel folds—the location of the page positions in relation to the gutter determined the degree to which parallel-fold pop-ups rose off the page.

Finally, we found that children conserved their troubleshooting-based knowledge of pop-up structure and function as instruction proceeded. For example, on day nine of instruction, Mr. R challenged the class to build angle-fold pop-ups so that they popped up as high as possible. Many children reported having no issues with this design challenge. Instead, they reported knowing how to solve the challenge based on their past experience with parallel folds. For example, Leslie reported, “I put it [the triangle] on the gutter because I know if it’s closer to the gutter, it would pop out more. The closer to the gutter the more it pops out. The further [from the gutter] the flatter.” Similarly, Alicia explained, “To make it pop high, you have to put the page positions close to the gutter.” These statements demonstrate how children conserved what they learned about pop-up structure and function through troubleshooting parallel-fold design challenges and used that knowledge to guide their solutions to angle-fold design challenges.

Summary: Reverse engineering and troubleshooting. To summarize, children reported identifying relationships between structural features and functional attributes of pop-ups during opportunities to reverse engineer and troubleshoot. Additionally, children linked their understandings about structural features of pop-ups to the nature and direction of pop-up motion.

Leading with the reverse engineering design challenge appeared to provide opportunities for children to participate in troubleshooting. In other words, reverse engineering and troubleshooting were complementary, and children often participated in reverse engineering and troubleshooting simultaneously. This exemplifies how ensembles of practice can emerge.

Part III: Drawing on Design Resources and Mechanistic Reasoning to Meet Design Goals

Children drew on design resources and on knowledge of structure-function relations to realize their design goals when building pop-ups. In the subsections below, we outline how children used specific folds in the service of storytelling, and how children used knowledge of pop-up structures to solve aesthetic problems when building pop-ups.

Children used specific folds in the service of telling stories. Some children reported using specific folds to help tell their stories. For example, Kara constructed her Peaches the Chicken pop-up so that it looked like Peaches was talking as the book opened and closed (Figure 7). To accomplish this, Kara designed Peaches so that her beak came together in a talking motion using two angle folds to replicate the up and down motion of the upper and lower beak.

When asked to describe her pop-up, Kara explained, “This is an angle [fold]. And I was wanting to make it like the alligator one where it would come up and meet it—so the chicken looks like it's talking.” This example demonstrates how Kara deliberately used her knowledge of the behavior of angle folds, and her understanding of how angle folds functioned in commercial books, to align her pop-up’s action with the action of the character in her story.

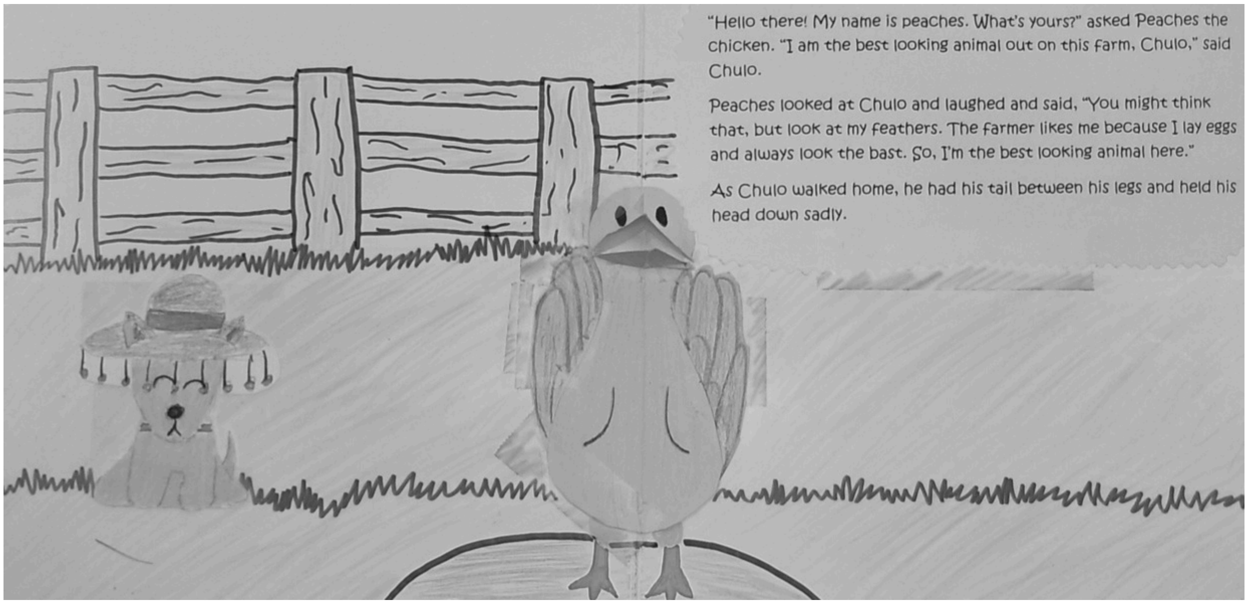

Figure 7. Chulo the Chihuahua meets Peaches the Chicken in a farmyard. The two angle folds composing Peaches's beak come together and move apart as the book opens and closes. Using angle folds in this way gives the reader the perception of Peaches talking to Chulo.

When asked to describe her pop-up, Kara explained, "This is an angle [fold]. And I was wanting to make it like the alligator one where it would come up and meet it—so the chicken looks like it's talking." This example demonstrates how Kara deliberately used her knowledge of the behavior of angle folds, and her understanding of how angle folds functioned in commercial books, to align her pop-up's action with the action of the character in her story.

Like Kara, Carissa used an angle fold in the service of telling her story. However, rather than using the angle fold to show a character's action, Carissa used it to highlight the position of a pop-up (her Summer Sun) in her story (Figure 8). When asked to describe her pop-up, Carissa explained, "And then here, I made another angle fold. And it's telling—in summer a lot of people like going for a swim—so I decided to put the setting as a beach. And the sun is always really high in the sky—so I put like—I wanted it to be out [of the book], because [if it were] in the corner [of one page], it would be kind of like hiding, so I wanted it to be high—so I did angle folds so they [the sides of the sun] come up." In her description, Carissa explained deliberately building her Summer Sun pop-up using an angle fold because it gave the perception of the sun being high in the sky. Moreover, Carissa reported selecting an angle fold because it helped illustrate her story better than if she simply attached the sun to one page of her book.

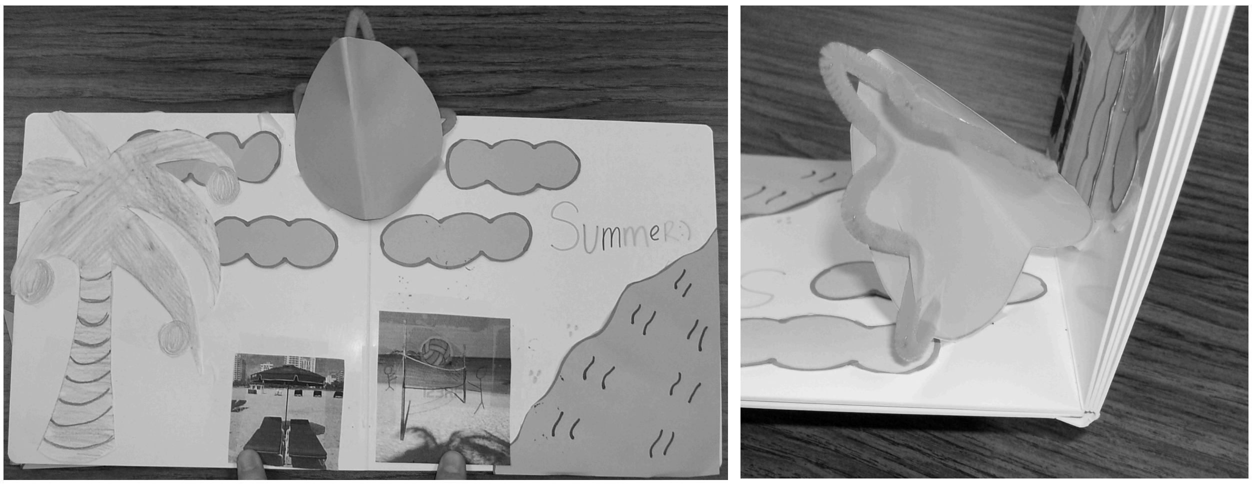

Figure 8. Two different views of Carissa's Summer Sun pop-up. The image on the left shows how the Summer Sun protrudes out of the book "high in the sky" when the book is open. The image on the right shows the page positions of the Summer Sun on either side of the gutter.

Children used knowledge of pop-up structures to solve aesthetic problems. Children sometimes used emergent knowledge of pop-up structure and function to solve what they perceived as aesthetic problems with their designs. For example, Mario used an asymmetric parallel fold to avoid creasing his Zombie Shake pop-up (see Figure 9). He explained that by using an asymmetric parallel fold, "whenever it [the book] folds, it [the pop-up] goes to the right, and it [the book] won't fold the actual pop-up." In using this technique, Mario blended understandings of pop-up structure and function (i.e., asymmetric parallel folds pop-up on one side of the book and fold somewhere other than the middle of the pop-up), which he learned through building and troubleshooting his first prototype pop-up, with a desire for his pop-up to look a particular way (i.e., he did not want the pop-up to have a crease down the center).

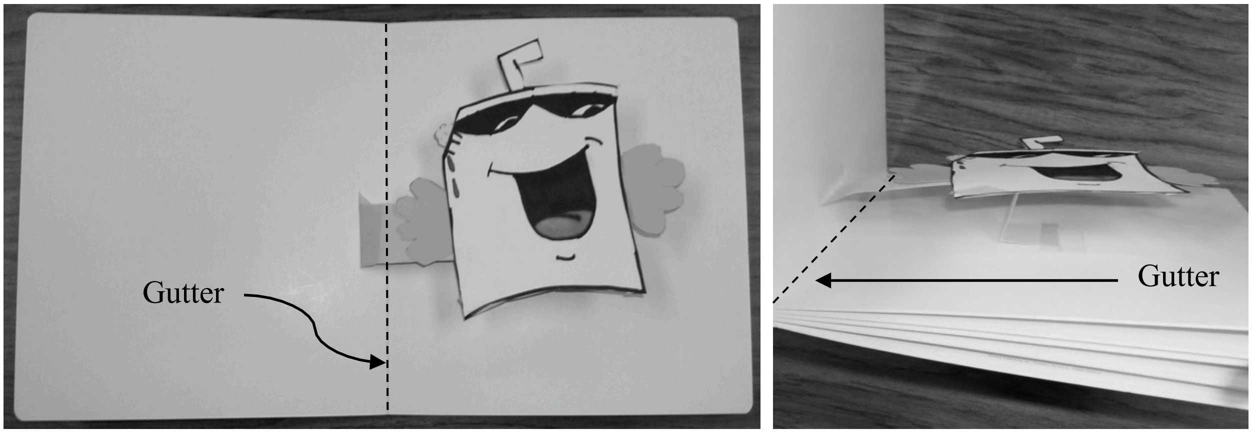

Figure 9. Two different views of Mario's asymmetric parallel-fold Zombie Shake pop-up. The image on the left shows the location of Mario's pop-up in relation to the gutter when his book was open. The image on the right shows the pop-up's page positions in relation to the gutter.

Continuities in design goals: Valuing aesthetic components. At post-interview, 54% of children reported valuing pop-ups that included aesthetic components such as objects, colors, and a high degree of pop. For instance, when asked if she thought any of her classmates made good pop-ups, Kara explained that Cole's pop-ups were good because they were "really [well] illustrated." Likewise, Janice reported liking Cedric's pop-ups because he was "a good artist." Similarly, Violet reported liking Emani's pop-ups because they were "colorful" and "pretty." Finally, Mario reported liking Jeff's angle-fold pop-ups because they "popped really high." These examples demonstrate that some children continued to consider many of the same aesthetic components of pop-ups to be key attributes distinguishing good from bad pop-ups.

Twenty-three percent of children also reported attempting to build pop-ups that were unique and creative at post-interview. For example, when asked why he used particular folds for the different pop-ups in his book, Mario reported that he wanted to create pop-ups that were different from his classmates' pop-ups. Furthermore, Mario also explained that he wanted to create pop-ups that were different from each of the other pop-ups in his own book. Kara echoed Mario's sentiments when she explained that she used different folds for the different characters in her book because she wanted "something different" and "something creative."

The role of reverse engineering in building pop-ups and writing stories. When we asked children if the reverse engineering design challenge helped them to design their final books, several children responded that the reverse engineering design challenge was helpful because it allowed them see how the pop-ups were attached inside the books and how the attachment points made a difference in how the pop-ups functioned. For example, Mario and Rosalie recalled examining commercial pop-up books to inform their decisions about how to attach pop-ups in their own books. Furthermore, Violet reported examining the structure of her classmates' books to find out how different functional aspects worked with the goal of incorporating similar functional aspects into her own book. Thus, engaging children in reverse engineering appeared to give them a resource for thinking about how to achieve functional features in their own pop-up books by examining the structural features in commercial books.

Summary: Design resources and knowledge of pop-up systems. To summarize, children drew on their knowledge of pop-up systems to solve aesthetic issues with their pop-up books and to help tell their stories. Furthermore, children maintained valuing aesthetic components of pop-ups and reported that the reverse engineering design challenge was helpful because it spurred them to investigate the relationship between pop-up structure and function.

Discussion

The recent introduction of the Next Generation Science Standards (Achieve, 2013) and related efforts suggest an increased emphasis on engineering practices in STEM education. In this study we aimed to contribute to this endeavor by investigating how children engaged in the practices of reverse engineering and troubleshooting by designing aesthetically pleasing pop-up books. Designing pop-up books gave children the opportunity to be expressive and to ground their designs in personal experiences and interests. In addition, participating in reverse engineering and troubleshooting helped children establish heuristics governing pop-up structure and function (e.g., points of attachment, direction of motion, and degree of pop). These in turn provided a practical grasp for expressing designs grounded in personal experiences and interests.

The forms of knowledge developed by students did not include the underlying algebraic relationships governing the properties of a fold. Instead, students often generated practical heuristics through literally grasping elements of a pop-up, such as its points of attachment. These resemble the forms of knowledge characterized as perceptual by Azevedo (2013) in his study of how hobbyists resolve problems of stability in their design of model rockets. What was worth grasping was informed by purposeful induction into practices of reverse engineering and troubleshooting to resolve design challenges. For example, in the original episode of reverse engineering, contrasting cases of type of fold were provided, and rather than simply noticing this difference, children were charged with reproducing how the folds worked. Reproduction inevitably involved tinkering with different locations in order to obtain the effect. Use of flags further highlighted perceptions and associations between types of folds and direction of motion. As children resolved a series of design challenges, variations in these perceptions led to the formation of heuristics, such as attaching the pop-up closer to the gutter to decrease the pop-up's motion. This perceptual knowledge served as a practical tool for personal expression.

Limitations

This study has several limitations. First, although we inducted children in the practice of reverse engineering and troubleshooting, describing prospective trajectories of growth in these forms of practice would require systematic revisiting of reverse engineering and troubleshooting for a more prolonged period of time. As it was, instructional time was limited by the requirement of accountability assessment in mathematics. Second, the number of paper engineering techniques we were able to introduce and systematically develop was limited. Performing more investigations of additional techniques would perhaps help children develop a larger repertoire of paper engineering skills they could draw on in service of design. Third, conversational and written exchanges in the class were a departure from everyday classroom practice. Thus, part of the instructional time was spent installing norms about interaction, especially critique. Hence, we did not fully exploit the utility of important social aspects of design, such as jointly investigating instances of failure or arguing for or against alternative solutions to design problems. Despite these limitations, pop-up book design evidently provided entrée to powerful approximations to productive engineering practices, such as troubleshooting and reverse engineering, and to aesthetic expression, by virtue of its open-endedness, familiarity, opportunities for artistic elaboration, and ties to narrative. Whether or not more elaborated forms of mechanistic reasoning could be developed with other representational means, such as those of digital technologies, or with opportunities to author more than one book, remains an open question.

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Appendix

Major Sources Children Drew from to Author Their Pop-Up Book Stories

Student	Topic	Commercial book	Library book	Personal life	Internet	Other interest
Sarah	A unicorn		X			
Dana	Poem about life			X		
Alvin	A wizard and his magic animals					X
Kiyara	Types of sports	X		X		
Abby	Exotic animals	X				
Gwen	Life as a cheerleader			X		
Adnan	Professional soccer players					X
Everett	A family of aliens					X
Ariel	Sinking of the Titanic		X			
David	My Little Pony®				X	
Violet	A young girl's birthday			X		
Leslie	Friendship			X		
Calvin	A pair of pants					X
Jorge	Nyan Cat				X	
Oscar	A ninja					X
Carissa	Earth's seasons	X				

Student	Topic	Commercial book	Library book	Personal life	Internet	Other interest
Zeb	A weird day			X		
Cedric	Types of sports	X				X
Clara	Spring	X				
Jeff	A taco who joins the circus				X	
Rosalie	An Adventure	X				X
Emani	Arkansas's seasons	X				
Alicia	The unicorn		X			
Karen	Jimmy Jet and his TV set		X			
Kara	Chulo the Chihuahua	X		X		
Mario	Scary stories		X			X
Janice	A bullied girl			X		
Leah	Summer	X				

CHAPTER IV

BUILDING AND TROUBLESHOOTING PAPER POP-UPS TO ACHIEVE AESTHETIC AND FUNCTIONAL GOALS

K-12 education in the U.S. traditionally entails teaching science, technology, engineering, and mathematics (STEM) as individual subjects (Sanders, 2009). This siloed model of STEM education has significant drawbacks. For example, it inadequately reflects the interconnected nature of the STEM disciplines, and it fails to promote synthesizing knowledge across STEM domains. In light of these and other shortcomings, the National Research Council (NRC, of the U.S. National Academies of Science) recently suggested the need for systematic exploration of the affordances and potential drawbacks of an integrated model of K-12 STEM education (Honey, Pearson, & Schweingruber, 2014). This recent report is consistent with previous proposals by the NRC to increase the presence of engineering in K-12 education (Katehi, Pearson, & Feder, 2009) and to incorporate engineering content and practices into existing STEM standards, rather than to develop separate K-12 engineering standards (NRC, 2010). This course of action was realized in the Next Generation Science Standards, which promote students learning crosscutting concepts and core ideas in science and engineering through engaging in shared practices, such as developing and testing models; engaging in evidence-based argument; and carrying out investigations to solve problems (Achieve Inc., 2013).

Although already underway, integrating science and engineering may prove challenging (Berland, 2013). There are several notable obstacles to integration. First, unlike K-12 science, K-12 engineering does not have an accepted canon (Katehi, et al., 2009). As a result, there is a lack of consensus about which engineering content and practices to emphasize in instruction. Second, there is a dearth of K-12 engineering education research (Brophy, Klein, Portsmore, & Rogers, 2008). Therefore, little is known about how K-12 students learn from participating in engineering practices. Third, the disciplines of science and engineering are based on different epistemic assumptions (Rouse, 2013; Williams, 2011). For example, both scientists and engineers evaluate models, however, they often do so for different reasons. Scientists usually evaluate models to explain phenomena (Gooding, 1990) while engineers usually evaluate models to determine how well they satisfy a need (Otto & Antonsson, 1991). Thus, integrating science and engineering may require negotiating differences in related yet distinct practices. In addition to these obstacles, it may also be difficult to find qualified individuals to teach integrated science and engineering, as there is not currently a system in place to educate engineering teachers and the majority of science teachers have little background in engineering (NRC, 2010).

Despite these obstacles, researchers have made progress integrating science and engineering education around *engineering design*, the systematic, iterative, and social process engineers use to solve problems (Bucciarelli, 1994; Dym, Agogino, Eris, Frey, & Leifer, 2005; Katehi et al., 2009; Simon, 1996). For example, researchers have used *design challenges*, activities where students design and build three-dimensional artifacts that perform a specific task or satisfy a set of constraints, to promote students learning a range of science concepts, such as force and motion (Kolodner et al., 2003), electromagnetism (Sadler, Coyle, & Schwartz, 2000), heat transfer (Schnittka & Bell, 2011) and ecology (Lehrer, Schauble, & Lucas, 2008). However, missing from these studies are inquiries into how students engage in engineering practices (e.g., reverse engineering, troubleshooting, and balancing trade-offs) coupled with investigation of how these engineering practices contribute to learning about science. Accordingly, in this paper, I investigate how students learn science and engineering concepts by designing, building, and troubleshooting paper pop-up books, otherwise known as paper engineering. Participating in paper engineering positions students to solve ill-structured problems (i.e., problems that possess conflicting goals and have multiple solution methods), a conundrum common in workplace engineering (Jonassen, Strobel, & Lee, 2006), while it also affords opportunities to investigate how simple machines work, a commonplace topic in most science curricula.

I focus on troubleshooting, the practice by which engineers diagnose faulty systems and then repair those systems so that they function normally (Jonassen, 2000; Jonassen & Hung, 2006), because it is common in engineering (Jonassen & Hung, 2006), and because it represents a reasonable approximation to professional practice. Practices are recurrent forms of activity, recognized and employed in a discipline to generate and revise knowledge. Hence, disciplinary practices are inherently epistemic (Knorr Cetina, 1999). Engaging students in engineering practices provides opportunities for them to experience how engineers establish, develop, and refine knowledge. Thus, when K-12 students engage in troubleshooting, they experience how professional engineers themselves build knowledge in their profession.

In addition to my interest in exploring how K-12 students learn by engaging in the practice of troubleshooting, I am also interested in more traditional concepts spanning science and engineering education. For example, I am interested in exploring how students come to understand structure-function relationships governing the mechanisms they build, as structure and function are crosscutting features of science and engineering (NRC, 2012).

Finally, I am also interested in investigating how K-12 students realize aesthetic goals when building mechanisms. I take aesthetics to be any visual, artistic, or stylistic element used to accomplish a design or to set one design apart from another. One hallmark of engineering design is that there are multiple ways to build an artifact to meet a set of specifications (Bucciarelli, 1994). This means that along with considering technical aspects when designing, engineers must also consider aesthetic aspects. In other words, understanding the technical aspects of a designed system represents only one facet of engineering design. However, I do not expect students to immediately take up achieving aesthetic elements as their primary design goal. Rather, I expect them to pursue self-expression, which approximates how a professional engineer might design with aesthetic goals in mind. Allowing students to design with the goal of expressing themselves is a stepping stone towards designing to achieve aesthetic goals with outside users in mind.

This study was guided by three research questions: (a) What is the nature of the pop-ups students build and what do students' designs indicate about paper engineering as a medium for self-expression? (b) What do students understand about pop-up structure and function? and (c) How does participating in the practice of troubleshooting contribute to students learning about pop-up structure and function? Next, I give an overview of the paper engineering context.

Paper Engineering as a Context for Engaging Students in Engineering Design

My investigation is based on a paper-engineering curriculum originally developed by Benenson & Neujahr (2009). In light of previous research suggesting that even when children can readily observe the parts of a mechanism, they often have difficulty understanding how it works (Bolger, Kobiela, Weinberg, & Lehrer, 2012; Lehrer & Schauble, 1998; Metz, 1991), Rich Lehrer and I revised Benenson and Neujahr's (2009) curriculum with an eye towards highlighting structure-function relationships and increasing the likelihood that students would take pop-up design as a forum for self-expression.

To highlight structure-function, we posed design challenges based on tasks students struggled with in a previous enactment of the paper-engineering curriculum. For example, we developed a design challenge in which we asked students to make their pop-ups pop up as much as possible, which was something students struggled with in the past. In addition, we initiated students into analysis of structure-function relationships by challenging them to reverse-engineer pages from commercially available pop-up books. Although seemingly simple, students' efforts to replicate the structure and function of these pages instigated unanticipated problems, which in turn created the need for participating in the related practice of troubleshooting. To promote reflection about structure-function, we asked students to record the problems they experienced during whole group discussions and to share how they solved the problems they encountered as they designed. Thus, troubleshooting and talking about troubleshooting became normative in paper engineering instruction. We conjectured that installing a normative practice of troubleshooting would help students solve the problems they encountered when designing their own pop-ups, while at the same time help them build technical knowledge of the pop-up system.

To increase the likelihood that students would view paper engineering as a vehicle for self-expression, we anchored designing in commercial products and in familiar literary resources such as Internet memes and graphic novels (Bransford, Brown, & Cocking, 2000). With the cooperation of the teacher, we also established an emphasis on "language arts" by including elements of narrative exposition and character development. Finally, rather than focusing on individual pop-ups, we encouraged the production of narratives that would integrate individual pages into a book that would engaging an outside reader, such as a sibling or a parent.

The revised paper-engineering curriculum consisted of a 10-lesson sequence in which students participated in various facets of engineering design by authoring and building their own pop-up books. Instruction began with students inspecting commercial pop-up books to discover: (a) which literary elements pop-up book stories included, such as characters, setting, and theme;

(b) how pop-ups were attached inside the books; and (c) how different pop-ups moved after opening and closing the books. Next, as mentioned previously, students were introduced to the practice of troubleshooting by participating in a reverse engineering activity in which they removed a pop-up from a commercial book and reattached it into a transparent book so that it worked correctly. Students then participated in a series of design challenges. During these design challenges, students explored how pop-ups operated, including how to: (a) attach pop-ups inside the book so that they pop up off the page, but do not protrude out of the book when the book is closed; (b) build tall and short pop-ups; and (c) build pop-ups that fold in the center of the book or on one side of the book or the other. Students then drafted stories and planned the layout of the individual pages of their own pop-up books. Finally, students assembled their books, which included writing a story and building five individual pop-ups. Students had considerable freedom to write their stories, but learned a limited number of folds to help them tell their stories via pop-ups. Next, I describe the features of the types of folds students learned during instruction.

Building Parallel and Angle Folds

Paper engineering employs two basic types of folds, parallel folds and angle folds. Parallel folds are composed of rectangular cardstock strips attached at points (i.e., page positions) parallel to the center of the book (i.e., the gutter) on either side of the page (see Figure 1, top). Moving the page positions towards the gutter causes a parallel fold to pop-up more (i.e., the pop-up becomes steeper), while moving the page positions away from the gutter causes a parallel fold to pop-up less (i.e., the pop-up becomes flatter). Parallel folds have a distinct “side-to-side” motion because opening the book causes them to move in an arc from right to left along the X-axis and up and down along the Z-axis.

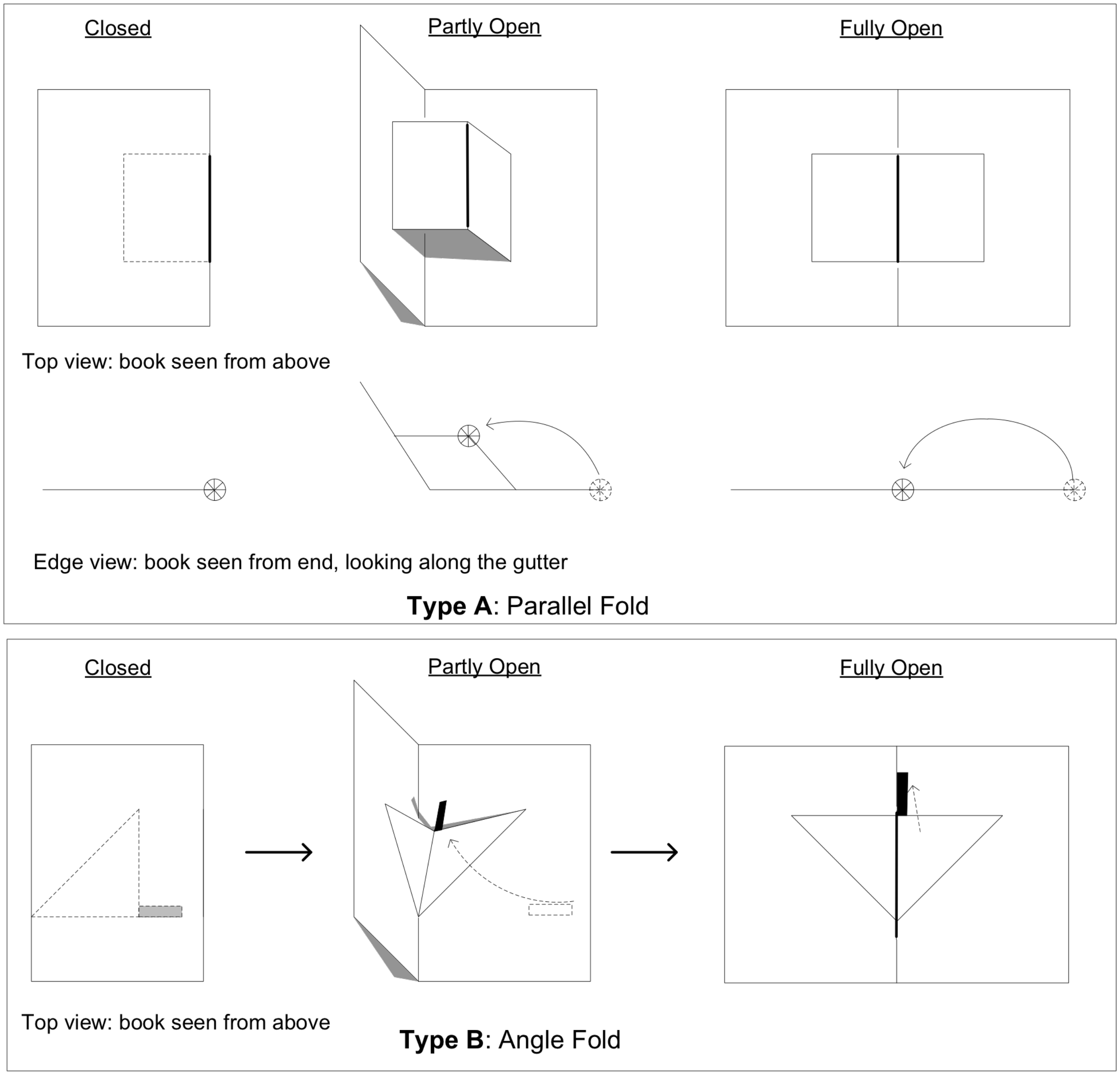


Figure 1. The two basic types of pop-ups (adapted from Benenson & Neujahr, 2009).

Angle folds are composed of triangular cardstock cutouts attached at page positions at an angle to the gutter (see Figure 1, bottom). Similar to parallel folds, decreasing the angle of the page positions in relation to the gutter causes an angle fold to pop-up higher (or steeper). In the same way, increasing the angle of the page positions in relation to the gutter causes an angle fold to pop-up less (or flatter). Angle folds have a distinct “up and down” motion because opening the book causes them to move in a an arc from right to left along the X-axis, up and down along the Z-axis, and from top to bottom (or from bottom to top) along the Y-axis.

Parallel- and angle-fold pop-ups can be symmetric or asymmetric. Symmetric pop-ups have page positions that are equidistant from the gutter, and always fold directly over the gutter. Asymmetric pop-ups have page positions that are not equidistant from the gutter. Asymmetric pop-ups have a near side, where the page position is closer to the gutter, and a far side, where the page position is farther from the gutter. Asymmetric pop-ups always fold on the far side.

Method

Setting and Participants

Participants included 12 boys and 16 girls from a seventh-grade math class in a suburban school located in a small southern city. The class was composed of 61% Hispanic, 25% White, 11% Pacific Islander, and 3% Asian students. The composition of the class was representative of the school. Additionally, 85% of students enrolled at the school qualified for free or reduced lunch. Together, the classroom teacher, Ms. C., and one researcher, Mr. R, led instruction.

Instructional Design

Instruction was based on a design experiment methodology (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). Researchers who conduct design experiments typically have two goals. First, they seek to engineer and study a particular kind of learning, often brought about by engaging students in an intervention refined across several iterations of use. Second, they attempt to develop domain-specific theories of learning that seek to do generative work in a field.

In the case of paper engineering, we aimed to support students participating in engineering design. Prior to this study, the paper-engineering curriculum underwent several iterations of use with students of different ages. For example, we used an earlier version of the instructional design in a fifth grade mathematics classroom. After each iteration, we evaluated the various successes and failures of implementation. We used what we learned to adjust the curriculum and accompanying resources to support students engaging in approximations of engineering practices such as troubleshooting.

At the same time, we also adjusted the paper-engineering curriculum to emphasize aspects of classroom activity we deemed important, such as writing and representing information. For example, students used engineering notebooks to document drawings of the mechanisms they built in class and to write summaries of class activity at the end of each lesson. Engineering notebooks were important resources for reminding students of what they learned in each class, and researchers frequently asked students to begin class by sharing information they recorded in their notebooks the previous day. In addition, we also organized instruction in paper engineering to emphasize students sharing work by engaging in small group and whole group discussions. For example, students often began by working on a task in small groups before coming together as a whole group to share and discuss the results of the task. Moreover, researchers promoted discussions by frequently using the classroom ELMO to project students' solutions so the rest of the class could see them. This allowed students to share results, ask questions, make claims public, and challenge one another's claims.

Finally, instruction in paper engineering revolved around students solving design challenges. When attempting to solve design challenges, students routinely built and tested prototypes. For example, students built prototype parallel-fold pop-ups before they built their final pop-up books. Building and testing prototypes was a venue for students to troubleshoot structural and functional problems within their pop-ups before building their final books.

Data Collection

Paper engineering instruction spanned 15 days. During this time, the class met once a day for approximately 45 minutes. To answer my research questions, I drew on six data sources: (a) daily classroom observations, (b) student-created artifacts, (c) pre- and post-instruction noticing interviews (d) design interviews, (e) post-instruction design interviews, and (f) teacher report, such as information about students' past performance on the statewide mathematics assessment.

Daily classroom observations. A videographer recorded all paper engineering instruction. Video records consisted of whole group and small group classroom activity. During whole group activity, the videographer moved back and forth between filming the teachers, who led instruction, and the students, who read from their notebooks, shared artifacts, and asked and answered questions. When the class transitioned from whole group to small group work, the videographer shifted the camera's focus to a single small group composed of four students who represented a range of mathematical ability. The videographer collected roughly 11 hours of video. Approximately half of the video followed students in their small groups.

Student-created artifacts. Students created a range of artifacts over the course of instruction. For example, students authored story maps, built prototype pop-ups, recorded observations in notebooks, and built pop-up books. I regularly photographed and scanned student-created artifacts to document what students produced. Additionally, with the exception of the final product, I collected all student-created artifacts.

Noticing interviews. Prior to and after instruction, I interviewed 8 students to determine what they noticed about pop-up structure, function, and aesthetics. I selected students based on Ms. C's belief that they would willingly share their thoughts and because they represented a range of mathematical ability based on the results of the annual statewide mathematics assessment. During these interviews, students saw five contrasting cases of pop-up design highlighting similarities and differences between structural and functional attributes of parallel and angle folds, such as: (a) page position, (b) direction of motion, (c) range of motion, and (d) height of the pop-up off the page (see Appendix A for a complete list of the paired comparisons). For each set of pop-ups, I asked students, What do you notice? and How are the pop-ups similar or different? Pre-instruction noticing interviews ranged from 9-17 minutes. On average, each interview lasted about 13 minutes. Post-instruction noticing interviews ranged from 11 to 24 minutes. On average, each interview lasted about 14 minutes.

Design interviews. Design interviews were one-on-one interviews conducted with individual students outside of instructional time. The design interviews were intended to elicit students' strategies for solving design challenges that we posed during the course of instruction in an individual context rather than the collective context of the classroom. Participants included students from the focus group as well as other students selected based on their willingness to contribute to class discussions. I completed two rounds of design interviews. In each round, I interviewed the same students to collect information about how they solved design challenges. Specifically, I interviewed students after they built prototype parallel folds and again after students built prototype angle folds. In these interviews, I supplied students with artifacts such as transparent books and cardstock strips to help them answer questions about the design challenges they completed in class. Questions included: Can you tell me about the design challenges we did? Did you have any issues when solving the challenges? and, How did you troubleshoot to solve those issues? Interviews ranged from 5 to 14 minutes. On average, each interview lasted approximately 10 minutes.

Post-instruction design interviews. After students finished building their final pop-up books, I interviewed them about their final products. The intention was to elicit what students found challenging about pop-up design and their reports of how they dealt with their challenges. Participants included the students interviewed in the two previous design interviews and six additional students. I selected these additional students based on Ms. C's recommendation and on their apparent interest in the project, demonstrated by their high level of participation. The impending end of the school year limited the number of post-interviews. Altogether, I interviewed 13 students. For each pop-up the student made, I asked questions such as: How did you decide to make that pop-up? Did you experience any issues building this pop-up? and Did you use troubleshooting to fix any issues? Post-instruction design interviews ranged from 7 to 28 minutes. On average, each interview lasted approximately 17 minutes.

Teacher report. At the end of the project, Ms. C. provided me with a range of supplementary information regarding the students in the class, including past scores on the annual statewide mathematics assessment, individualized education program (IEP) status, and English language learner (ELL) status. Furthermore, to become acquainted with students' dispositions towards schooling in general, I also asked Ms. C to write short biographies for several of the students in the class. Each biography included information about: (a) academic background, (b) personal background, (c) school social life, (d) Ms. C's initial expectations for how the student would participate in the project, (e) Ms. C's reactions to how the student performed in the project, and (f) other information Ms. C viewed as pertinent.

Analysis

Research question I. To answer my first research question (i.e., What is the nature of the pop-ups students build and what do students' designs indicate about paper engineering as a medium for self-expression?), I began by inspecting photographs of students' pop-ups and classifying them based on a number of observable characteristics (see Table 1 for a list and description of these characteristics). For each page in a student's pop-up book, I noted the: (a) type of fold used (e.g., parallel or angle, symmetric or asymmetric), (b) number of pop-ups, (c) connectivity of the pop-ups (e.g., connected in parallel or in series), (d) paper strip composition (e.g., standard strip, strip cut into a shape, or strip composed of a printed picture), and (e) method of illustration (e.g., markers and pencils, cardstock cutouts, printouts). My rationale for collecting this information was that I consider variability in production as indicators of student engagement and expression. For example, one might conceive of students who merely followed directions in class without investing much effort or interest in the project. If this experience of noninvolvement were normative, then I would expect little variation, perhaps observing only one type of fold and little effort to customize the material provided.

Table 1

Observable Characteristics of Pop-Ups

Characteristic	Description
Type of fold	Parallel or angle, symmetric or asymmetric
Number of pop-ups	Number of pop-ups on the page
Connectivity of pop-ups	Connected in parallel or in series
Paper strip composition	Standard strip or custom strip
Method of illustration	Marker and pencil drawings, cardstock cutouts, or printouts

For pop-ups that were difficult to identify how they worked based on a picture alone, I searched for video footage in which the students who built them explained how they worked. In addition, I also recorded the range of topics students covered in their pop-up books such as, sports, pets, insects, wizards, aliens, and unicorns. See Appendix B for the full range of topics about which students authored their books.

Next, to better understand students' motivation for authoring their books and to better characterize the choices students made when designing their books, I developed case studies of how two students authored, designed, and built their books. I selected the two students based on the supplemental material provided by Ms. C and on the different approaches each student had towards authoring and building pop-up books. To develop each case, I drew from information in students' story maps, photographs of students' finished pop-up books, and excerpts from post-instruction design interviews in which students discussed their finished books.

Research question II: To answer my second research question (i.e., What do students understand about pop-up structure and function?), I first analyzed interviews in which students: (a) described how their pop-ups functioned and (b) explained how they solved problems they faced while building their pop-ups. To complete this analysis, I began by transcribing the: (a) first round design interviews (n = 7), (b) second round design interviews (n = 7), and (c) post-instruction design interviews (n = 13). Next, I imported the interviews into a video analysis tool, *Studiocode 5*, which I used to trim each interview to a unit of analysis. For the unit of analysis, I selected the set of questions from each interview that prompted students to talk about their pop-ups and to explain how they solved the problems they encountered when building their pop-ups. Table 2 outlines the questions that comprised the unit of analysis for each interview. Altogether, I isolated 69 units of analysis (i.e., 7 from the first design interview, 7 from the second design interview, and 55 from the post-instruction design interview).

Next, I developed a coding scheme to characterize student learning about structure and function (see Appendix C for the complete coding scheme). To do this, I began with a template which I developed based on the different design challenges in which the students participated. Next, I watched a random sample of interview instances (20% across the three different interviews) to refine my existing codes. After developing the coding scheme, I used *Studiocode 5* to code all of the interview instances. I performed reliability by asking an independent coder to code a random sample (20%) of the interview instances. Reliability was 93%.

Table 2

Interview Questions Included in the Unit of Analysis

Design Interview		
Design I	Design II	Post-instruction Design
1) Can you tell me about the parallel-fold challenges we have done in class? 2) Did you have any issues making parallel folds? 3) How did you troubleshoot to solve those issues?	1) Can you tell me about the angle-fold challenges we have done in class? 2) Did you have any issues making angle folds? 3) How did you troubleshoot to solve those issues?	1) Can you tell me about this pop-up? 2) Did you have any issues or problems when making this pop-up? 3) How did you troubleshoot to fix those issues?

Finally, I compared students' pre- and post-instruction noticing interviews. To do this, I began by watching each of the pre-instruction noticing interviews and developing a coding scheme meant to characterize trends in what children noticed when inspecting different commercial pop-ups. The coding scheme I developed included five categories: (a) student discussed pop-up book objects or colors, (b) student discussed pop-up directional motion, (c) student discussed the degree to which the pop-up extended out of the book, (d) student discussed pop-up size and complexity, and (e) student discussed aspects of pop-up structure, such as attachment to the page. After developing the coding scheme, I coded each of the pre- and post-instruction noticing interviews. I then compared the results to determine if students reported changing their notions of pop-up structure-function relationships as a result of instruction.

Research question III: To answer my third research question (i.e., How does participating in the practice of troubleshooting contribute to students learning about pop-up structure and function?), I watched all the whole group instruction video and developed content logs for each lesson using *InqScribe*. Next, I wrote memos based on each content log in which I documented: (a) design challenges, (b) problems researchers posed, (c) solutions students discovered, and (d) statements students made about how their pop-ups worked. From these, I selected three instances to illustrate what students learned about how their pop-ups worked.

The first instance was from the beginning of instruction when students were introduced to the practice of troubleshooting by completing a design challenge in which they reverse engineered a pop-up. Figure 2 shows the two pop-ups students reverse engineered in this challenge. The first was a parallel-fold pop-up of a dog, and the second was an angle-fold pop-up of a bird's beak. During the challenge, students troubleshot a variety of problems they experienced, such as how to attach the pop-up to the page.

The second instance was from early in instruction when students participated in several parallel-fold design challenges (i.e., students attached cardstock strips into transparent books to replicate features of the parallel folds they saw in commercial books). During these challenges, students troubleshot to solve issues such as how to prevent pop-ups from protruding out of a closed book and how to make tall and short pop-ups.

The third instance was from later in instruction when students participated in several angle-fold design challenges (i.e., students attached cardstock triangles into the same transparent books to replicate the features of the angle folds they saw in commercial books). During these challenges, students faced problems similar to those they faced when solving parallel-fold design challenges (e.g., how to build tall and short, and symmetric and asymmetric pop-ups).

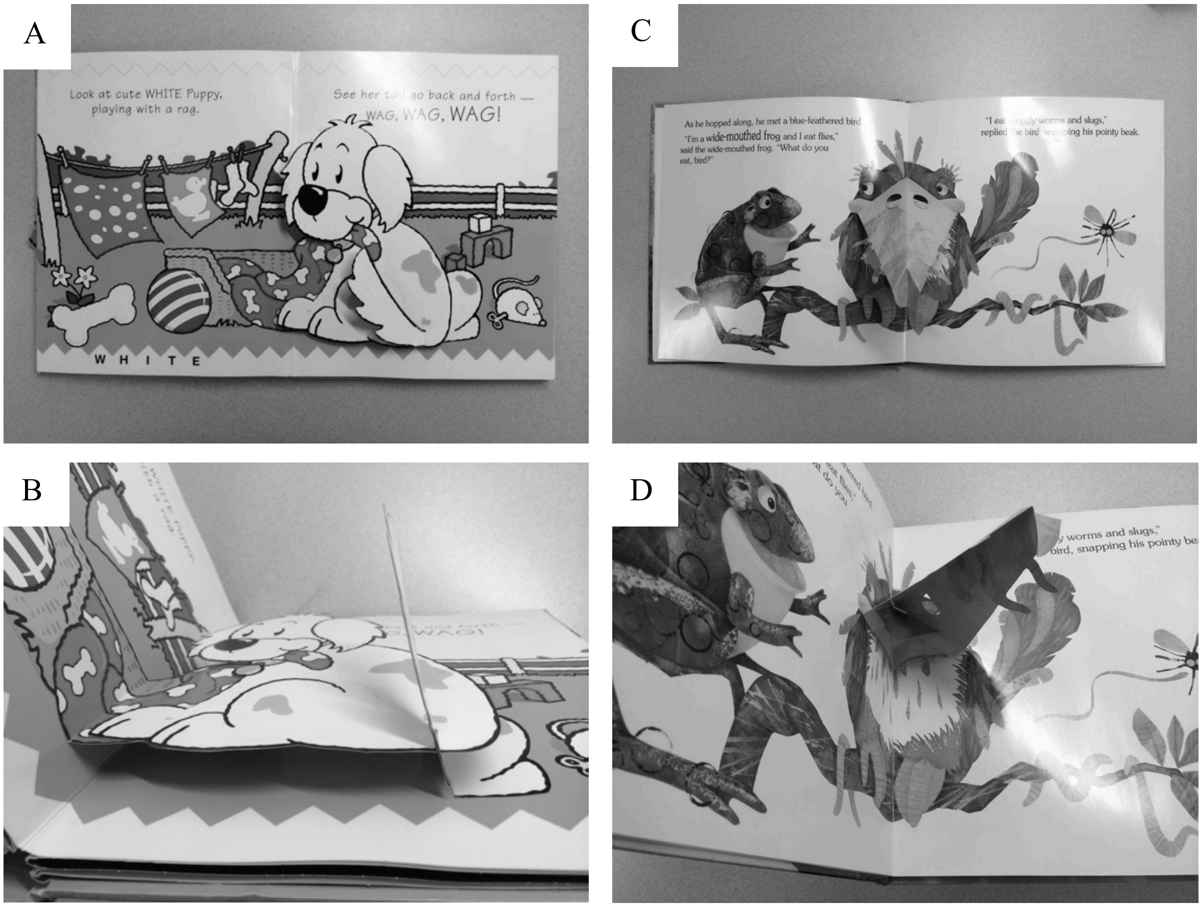


Figure 2. A) Parallel-fold dog pop-up (Lee & Repchuk, 1998). B) Side view of parallel fold. C) Angle-fold bird beak pop-up (Faulkner, 1996). D) Side view of angle fold.

Results

I present the results in three parts. Each part aligns with one of my research questions. First, I explain the nature of the pop-ups students built. Second, I report what students understood about pop-up structure and function. Third, I explain how participating in the practice of troubleshooting contributed to students learning about pop-up structure and function.

Part I: What is the Nature of the Pop-Ups Students Build and What do Students' Designs Indicate about Paper Engineering as a Medium for Self-Expression?

The 28 students who participated in paper engineering built 124 pop-ups on 104 pages. Students produced a range of one to five pages per book (M = 3.7, SD = 1.3), with a range of one to three pop-ups per page (M = 1.2, SD = .5). Twelve students (43%) incorporated pages in their books that included more than one pop-up. Altogether, these 12 students produced 16 multiple pop-up pages. Seventy-five percent of these pages included two pop-ups and 25% included three pop-ups. Of the pages with two pop-ups, 25% included two parallel folds, 50% included two angle folds, and 25% included one parallel fold and one angle fold. Of the pages with three pop-ups, 50% were composed of three angle folds, 25% were composed of one parallel fold and two angle folds, and 25% were composed of two parallel folds and one angle fold. All of these multiple pop-up pages consisted of pop-ups connected in parallel.

Fifty-four percent of the pop-ups students built used parallel folds and 46% used angle folds. Of the parallel-fold pop-ups, 39% were symmetric and 61% were asymmetric. Of the angle-fold pop-ups, 77% were symmetric and 23% were asymmetric. Furthermore, 96% of students incorporated one or more parallel folds into their books, while 86% of students incorporated one or more angle folds. Only five students (18%) built books in which they did not use both parallel and angle folds. Of these five students, only one finished more than two pages.

Apart from using different types of folds and varying the number of pop-ups on each page, students also used different techniques to customize the paper strips they used for making their pop-ups. For 66% of the pop-ups built, students used a paper strip with an image or character attached to it. Figure 3A illustrates how one student, Janice, used this technique in her book. For the remaining 34% of the pop-ups built, students cut paper strips into specific shapes before attaching them into their books. For instance, rather than attaching her Moo Moo the Cow pop-up to a rectangular strip, Kara instead drew Moo Moo's head, cut it out, and then attached it onto the page (Figure 3B). By doing this, Kara customized her strip. Of the pop-ups in which students built customized strips, 19% were composed of an image they printed from the Internet (for example, see Emani's penguin pop-up in Figure 3C), suggesting that our intention to embed student design in the larger world of print and graphic design was appropriated by students.

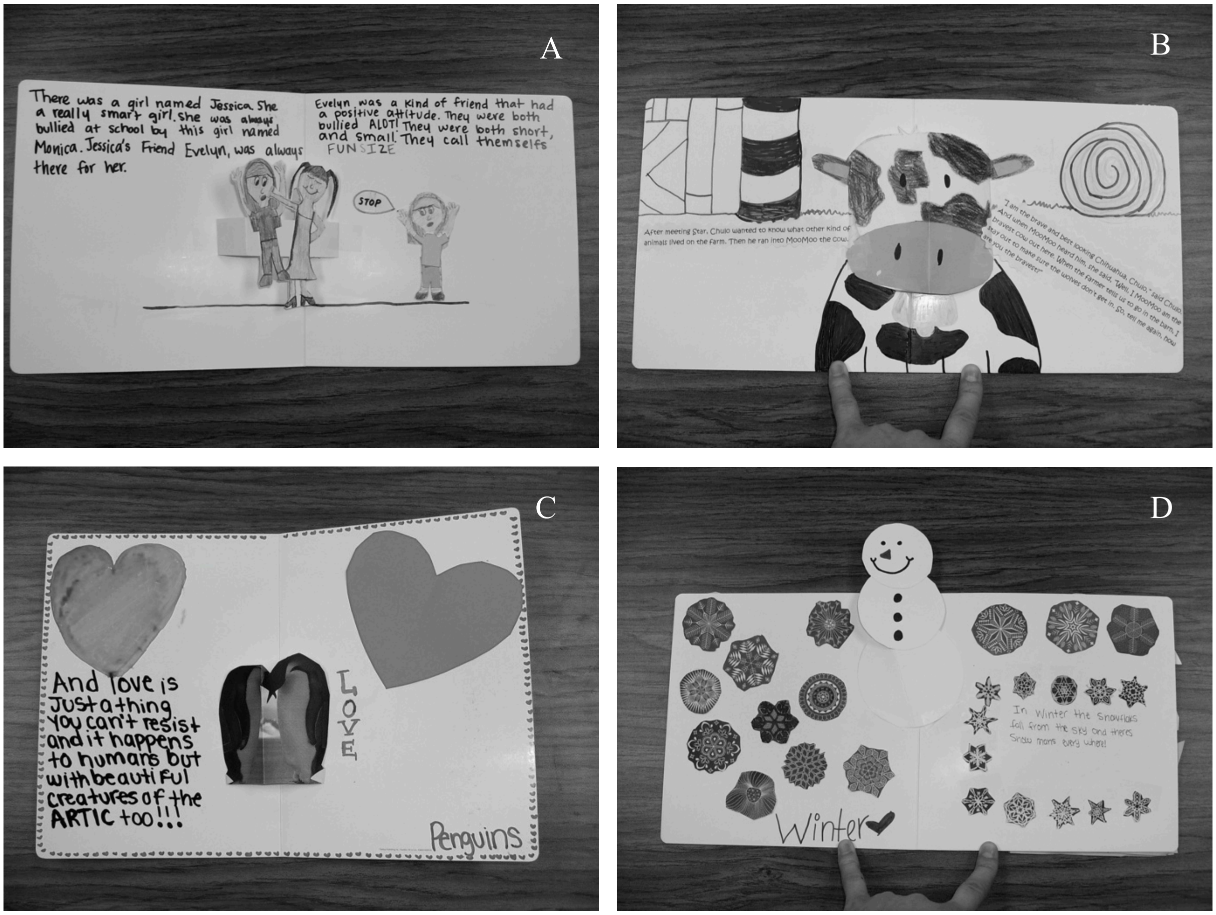


Figure 3. A) Janice illustrated her characters, cut them out, and then attached them to an asymmetric rectangular strip. B) Kara customized a parallel fold in the form of a cow's head. C) Emani used a printed picture of two penguins as her strip. D) Carissa printed images of snowflakes, cut them out, and then pasted them to the page.

Students also used a number of different techniques to illustrate the pages of their books. The most popular way for a student to illustrate his or her page was to draw directly on the page with marker or pencil. Students illustrated 61% of the pages they built using a combination of marker and pencil. In addition to illustrating pages using marker and pencil, students also illustrated 47% of the pages they built by cutting figures out of construction paper and then pasting them onto the page. Finally, students illustrated 28% of the pages they built by printing pictures from the Internet and then pasting them onto the page. For example, in her book about the Earth's seasons, Carissa printed, cut out, and pasted 25 snowflakes onto her winter season page (Figure 3D). Thirty-six percent of the pages students built incorporated two or more of these illustration techniques, which accounts for these percentages totaling over 100%.

Finally, students composed stories based on a variety of activities and interests. For example, 29% of students (n = 8) based their story on their own lives (e.g., Janice wrote about her experience being bullied for being small and smart and Kara wrote a fictional story based on her dog, Chulo, traveling around her farm meeting other animals), 21% of students (n = 6) based their story on fantasy (e.g., Alvin wrote about a mysterious wizard and Everett wrote about a family of aliens), and 14% of students (n = 4) wrote about playing sports (e.g., soccer and cheerleading). I detail two of these stories further in the contrasting case studies that follow. The first case study documents how a high-achieving student built her pop-ups, and the second case study documents how a struggling student built his pop-ups. These contrasting cases are meant to illustrate the affordances of paper engineering for students with different academic profiles and to show how students valued different components when creating pop-ups.

Case study I: Janice. Janice was a 12-year-old Hispanic girl who lived with her mother, father, and siblings. Neither of Janice's parents spoke English fluently, and she was classified as an ELL 4 long-term student, which meant she had a high-intermediate command of English. In each of the past two years, Janice scored the highest in her class on the statewide mathematics assessment and was classified as advanced. Janice's teacher, Ms. C, described her as a top student who always tried her best. Ms. C was not surprised by Janice's eager participation in the pop-ups project as she expected her to engage with the material and build satisfactory pop-ups.

Janice's pop-up book. Although Janice completed a detailed story map, which included text for each of the five pages, and worked assiduously on building her pop-ups during the time allotted, she did not finish building all the pop-ups or adding text to all of the pages in her book. For the pop-ups Janice did build, she was able to identify the folds she used, provide rationale for why she used them, and describe how they helped tell her story. On the whole, Janice stuck to the story she originally planned. She also spent a great deal of time working on the figures she attached to the folds she made, meticulously drawing, coloring, and cutting them.

The title of Janice's book was *The Girl That Never Gave Up* and the main character in Janice's story was a young girl named Jessica who was bullied at school for being small and smart. During the interview Janice indicated to me that the character of Jessica was based on her own experiences as a small smart student who had been bullied in the past. The first page of Janice's book showed Monica, the bully, pushing Jessica down to the ground with Evelyn, Jessica's friend, standing nearby imploring Monica to stop. On this page, Jessica narrated the events with almost the exact same text she recorded in her story map (Figure 4).

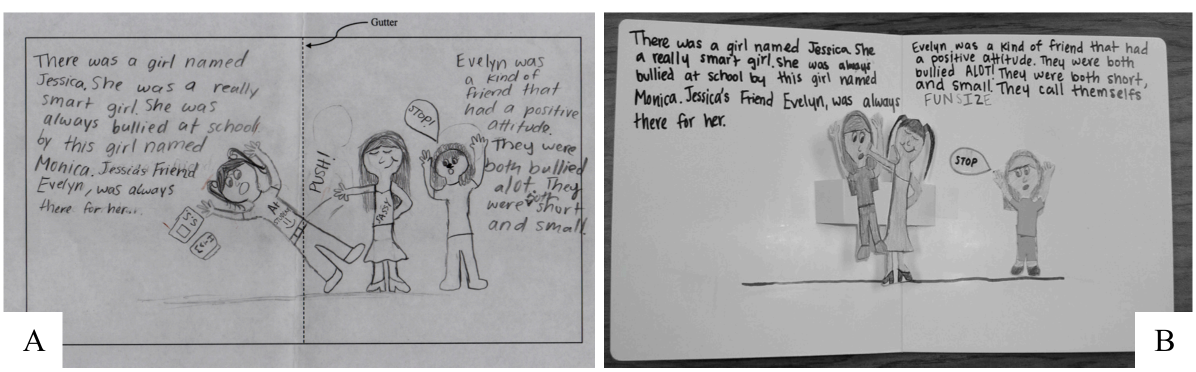


Figure 4. A) The first page of Janice's story map. B) The first page of Janice's pop-up book.

When I asked Janice to describe the pop-up she built on the first page of her book, Janice explained, "This is a parallel fold because it's over the gutter and it has a long strip, not a triangle." I followed by asking Janice if she experienced any issues making her pop up. Janice responded that she did experience an issue with how to correctly attach the pop-up’s page positions, which she solved with help from Ms. C. The transcript of this episode appears below.

Mr. R: So how did you figure out where to put them [the page positions]?

Janice: I had help from Ms. C.

Mr. R: And what did she say?

Janice: She tried to put it [the strip] on one side [gestures asymmetric page positions] 'cause mostly parallel folds, not mostly, but some of them are at one side [gestures to the left side of the book], and some are the other side [gestures to the right side of the book] and some are the middle, but if you put it in the middle, it would be a mountain, and it's better off to be a side.

Mr. R: You didn't want a mountain there [the center of the book]? When you say mountain, what do you mean by mountain?

Janice: It would be tall [puts palms together and gestures up].

In this instance, Janice demonstrated understanding the difference between symmetric and asymmetric parallel folds and explained not wanting her parallel fold to pop up symmetrically (i.e., like a mountain) directly over the center of the book. Although it is unclear why Janice preferred an asymmetric parallel fold for her pop-up, she did report selecting a specific type of fold based on the particular attributes of that fold.

Although Janice worked hard to align the second page of her book with her story map (Figure 5A), she was unable to completely finish building the page. While Janice did attach two parallel folds to the page and place a figure of Jessica sleeping in a bed on the lower fold, she did not add text to the page or attach the window and curtains to the top parallel fold (Figure 5B).

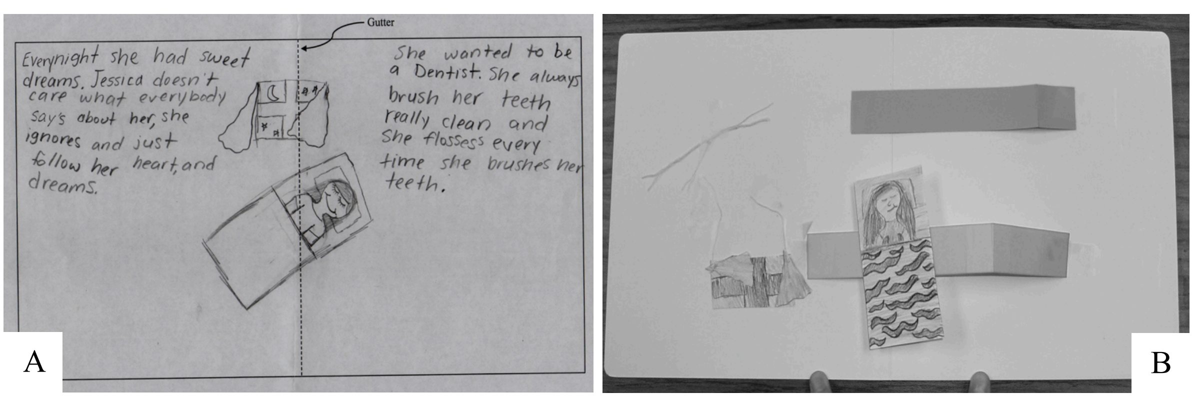
When I asked Janice to describe how her second pop-up helped tell her story, Janice explained, “Because she's [Jessica’s] like a smart, she's a smart girl and she likes to learn a lot and her goal is to be a dentist so she's learning a lot. She likes having dentist appointments, learning a lot. Like she asks them questions a lot. And she has dreams about her being grown up and she doesn't care what other people say. She just follows her dreams.” Once again, Janice’s description demonstrated that she tended to stay close to her original story map when building her pop-ups. In addition, Janice went on to describe intentionally attempting to coordinate the type of the fold she used with the action occurring in her story (see transcript below).

Janice: This is her [Jessica] sleeping and she has good dreams and I wanted to make the window right here sway. And I couldn't do it with an angle fold 'cause it would go up and down. But I wanted the curtains to sway.

Mr. R: So why did you choose a parallel fold for that one?

Janice: Because normally parallel folds sway a lot, side to side.

Here, Janice explained wanting the curtains to have a particular type of motion. Therefore she decided to use a parallel fold because it moved from side-to-side rather than an angle fold, which moved up and down. In this instance, Janice made a choice about what kind of pop-up to put in her book based on its aesthetic attributes and how they aligned with the action in her story.



A B

Figure 5. A) The second page of Janice’s story map. B) The second page of Janice’s book.

The third page of Janice's book consisted of two figures, Monica and Jessica, attached to a single asymmetric parallel fold. Janice clarified that the third page was meant to show the moment when Jessica got tired of being bullied. Janice explained, "She's [Jessica's] been bullied a lot of her years because she was short. And she needed to step up for herself. Her friend wasn't there, she was sick. And so she stood up for herself. 'Stop! I'm tired of it! I'm tired of getting bullied!' And Monica was shocked 'cause she didn't know that she would stand up for herself."

When I asked Janice if she troubleshot to solve any problems when building her third pop-up, she reported, "Yeah. I was thinking which side do I want to make it [fold on]? And I decided [to make it fold] on the left so I put a little bit right here [gestures to the right page position near the gutter] and the rest of it here [gestures to the left page position far from the gutter] so it's asymmetrical." Thus, once again, while it is unclear what drove Janice's decision, she demonstrated understanding how to build an asymmetric parallel-fold pop-up.

The fourth and fifth pages of Janice's book each consisted of asymmetric parallel folds attached into the book, but were otherwise incomplete. When describing what these pages were meant to show, Janice explained, "Monica, she said sorry and then... she's been bullied, too. Not any more 'cause she's one of those popular girls, but before, she was made fun of whenever she was in kindergarten for being so tall. They called her tree and stick. And she's also skinny. And then Jessica, she's not one of those bad people that um, doesn't forgive. She likes to forgive. And she said it's OK, let's just be friends, or even more than friends, best friends. And then Monica decided to say OK 'cause she had also got tired, and so, they became friends."

Summary: Janice case study. In this case, Janice, a high-achieving student who the teacher expected would do well in the pop-ups project, engaged seriously with the material in the pop-ups curriculum to author a story based on a deeply personal experience. Although Janice didn't finish her book, she worked diligently and modeled her book on the draft she wrote in her story map. In addition, Janice explained knowing how to build symmetric and asymmetric parallel folds and purposefully selected folds based on their aesthetic and functional attributes.

Case study II: Alvin. Alvin was a 13-year-old Caucasian boy who lived with his mother, father, and brother, all of whom were native English speakers. Alvin's scores on the statewide mathematics assessment had dropped from advanced to proficient over the past year. His teacher, Ms. C, described Alvin as a student who seldom participated in class, often worked alone, rarely turned in homework, and consistently earned poor grades. Ms. C did not have high expectations for Alvin at the beginning of the project and was quite surprised to find him making pop-ups, regularly sharing his thoughts with the class, and working well with his group members.

Alvin's pop-up book. Rather than complete a story map with text and pictures for the different pages of his book, Alvin wrote the beginnings of a much longer story based on a subject he knew a lot about, wizards. When building pop-ups, Alvin worked quickly and sometimes discarded finished pop-ups in favor of building something more interesting. As a result, when Alvin finished his book, although it maintained his original theme, the story differed from the original. During the post-instruction design interview, Alvin sometimes talked about the different types of folds he used in his book, but was much more inclined to explain his story.

The title of Alvin's book was *The Wizard Killer* (Figure 6A). Although Alvin initially planned to make the main characters of his story a boy named Jake and his girlfriend Maria, he eventually adopted a technique he saw used in several of the commercial books where each page of the book depicted one character and focused on only that character. The first page of Alvin's book showed a wizard performing magic with his scepter (Figure 6B).

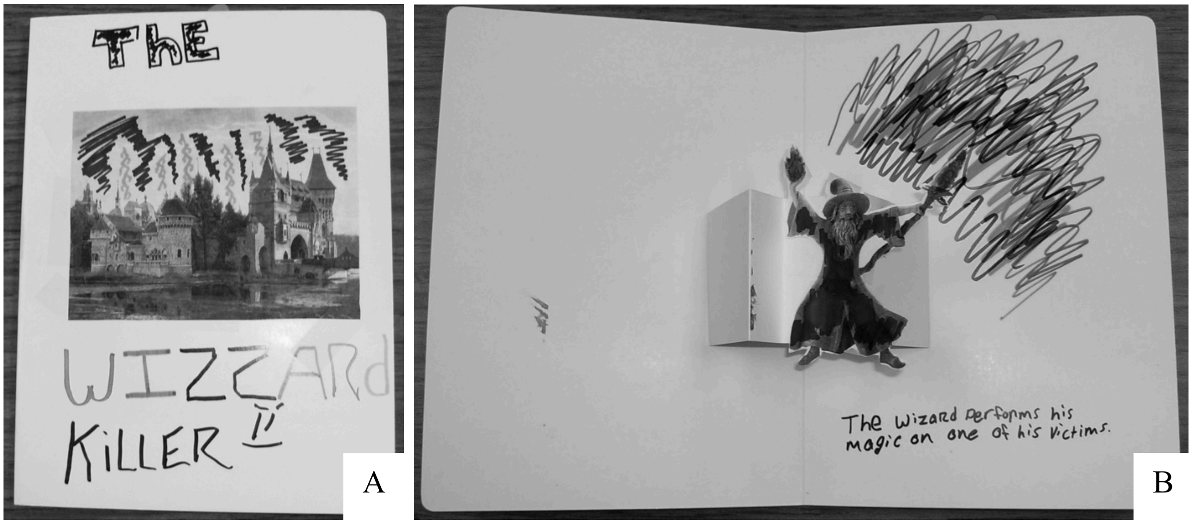


Figure 6. A) The cover of Alvin's book. B) The first page of Alvin's book.

When I asked Alvin to explain the pop-up on the first page, Alvin responded that the wizard lived in a mansion and didn't like intruders. Alvin continued to explain that the different colors coming from the wizard's scepter represented different spells he used on intruders.

Alvin: The green is, it forms plants inside of your body to grow, and it hurts every time you, like a root grows.

Mr. R: I bet. Yeah.

Alvin: And then the green, the blue is, it makes you go blind. The bright green is, it is like a blast of ice and makes you freeze for a few days. And if you survive, or if he decides to let you go, and give you a different condition, then he'll use the red. And the red is like fire and if he uses his ice first, then it would melt. But if he doesn't, then it'll just burn you. And then, I think if you made purple right here, then it would, the purple would be different conditions of all of them.

Mr. R: Uh huh. Then that would probably be bad.

Alvin: Yeah. 'Cause then you have plants growing out of you, you're frozen, and you're caught on fire. And you're blind. So you don't know what's happening.

This excerpt demonstrated how Alvin was primarily interested in discussing his story during the post-instruction design interview. Moreover, it also illustrated how his story was evolving. Basically, for Alvin, the story changed all the time as he imagined more and more interesting things that might happen with the characters at every moment.

Eventually, Alvin came around to describing the different magical animals the wizard kept in his castle. The second, third, and fourth pages of Alvin's book each focused on one magical animal. The first was a snapping turtle (Figure 7A), with an unbreakable protective shell that turned to iron when stabbed with a sword, the second was a ferocious bear with continuously growing teeth, a result of a spell the wizard cast on him (Figure 7B), and the third was a snake.

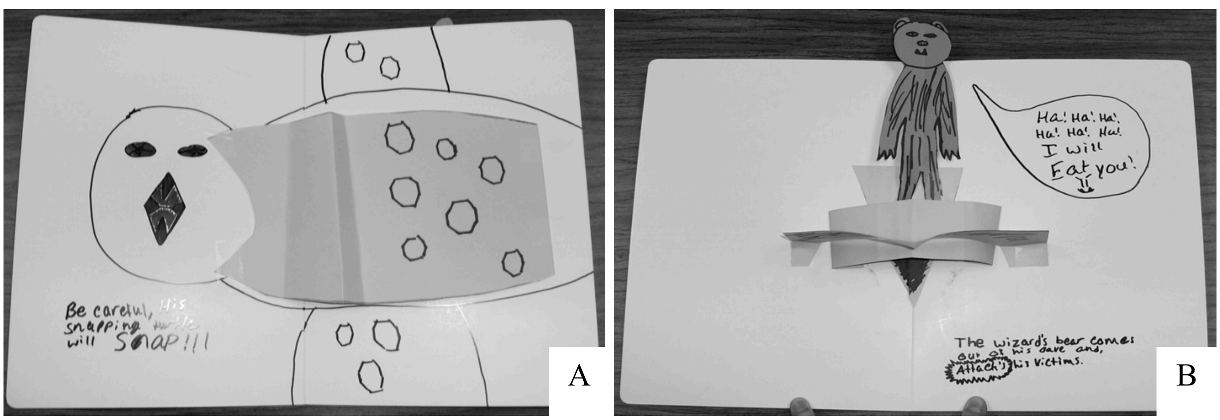


Figure 7. A) Alvin's magical snapping turtle pop-up. B) Alvin's magical bear pop-up.

Alvin spent a great deal of time talking about the animals who lived in the wizard's castle, and he was happy to answer questions about their magical powers, but when I attempted to find out why Alvin used particular folds to build his different pop-ups, he was less interested in sharing information. For example, as Alvin was explaining the snapping turtle's powers I asked him to describe how he decided to make the pop-up (see transcript below).

Mr. R: Tell me about the protective shell and the fold that you made.

Alvin: It was kinda supposed to be a parallel fold but then I had to force the book to close it. And so I just made it an angle fold.

Mr. R: Did you have any issues or anything with that one?

Alvin: At first in, the folds didn't really want to fold at all... And the shell, what it does for the turtle is provides it protection, so if you have, if you have a sword on you, and you, you try to kill it, like stab it or something, then it's shell will just turn into, it turns into iron and it's like the wizard made it unbreakable.

In this instance, Alvin explained that he initially meant to make a parallel fold, but instead, unintentionally made an angle fold. In other words, the book did the computational work of folding his pop-up for him. This turn of events did not seem to concern Alvin, and showed that for him, pop-up structure came second to story. After he explained accidentally making an angle fold, Alvin seamlessly returned to describing characteristics of the snapping turtle's magical shell, demonstrating once again that he was chiefly interested in the story.

In another episode that followed shortly after, I asked Alvin if he experienced any issues when making his bear pop-up. Alvin responded, "Yeah. I couldn't decide how to get a fat bear." This instance demonstrated that even when Alvin did experience problems building his pop-ups, they had to do with aesthetic rather than functional aspects. That is, Alvin's response focused on the problems he had realizing his vision for the bear—and not for the fold.

The last page of Alvin's book depicted a hostage escaping from the castle after being tortured by the wizard. His skin had red, blue, green, and black patches where the wizard's spells hit him. Here again, Alvin demonstrated how interested he was to talk about his story.

Alvin: Right here, I mean right here [gestures to a red patch of skin], he got burned kind of. And then right here, the blue, was that he got frozen in those spots.

Mr. R: Oh was it like he got hit by the wizard's....

Alvin: Yeah. It gave him frostbite in those spots. The brown is just like his skin color. The green was the, it was a mix of two kinds of powers and it left a mark right there. The black was of all of the wizard's powers. He combined them to make something that hurt, like really bad. And the red, the wizard burned his feet.

Summary: Alvin case study. In this case, Alvin, a struggling student who the teacher expected might not have success in the pop-up project, eagerly authored a story about a mysterious wizard. When describing the pages of his book, Alvin repeatedly demonstrated how important the story was to him and how the story constantly evolved to include interesting attributes he imagined about the characters. Additionally, Alvin demonstrated modeling his book on the structure of several of the commercial books in the class set. Finally, Alvin demonstrated that for him, how his pop-ups looked was more important than how they functioned.

Part II: What do Students Understand About Pop-Up Structure and Function?

Across 69 units of analysis, I recorded 82 codes (i.e., 19 in the first design interview, 16 in the second design interview, and 47 in the post-instruction design interview). The number of codes per unit of analysis ranged from 0 to 5 (M = 1.18, SD = 1.21). Across the three interviews 33% percent of codes referenced basic structure, 18% referenced symmetric and asymmetric pop-ups, 17% referenced direction of pop-up motion, 15% referenced keeping the pop-up in the book, 11% referenced pop-up height, and 6% referenced magnitude of pop-up motion. The seven units of analysis in the first interview accounted for 23% of the codes applied, the seven units of analysis in the second interview accounted for 20% of the codes applied, and the 55 units of analysis in the third interview accounted for 57% of the codes applied.

Design interview one. In the first interview, students discussed the parallel-fold challenges they completed. Seventy-one percent of students (n = 5) explained that parallel folds must span the gutter and attach to the right and left pages of the book. Of these students, 60% (*n* = 3) explained that for pop-ups attached to both pages of the book, opening the book caused the pop-up to transmit motion. For example, Alvin explained, “At first, I didn’t know how to make them [parallel folds] pop-up. And then I figured out that if we tape them onto each side of the page then they’ll pop-up better than if you tape them to one side...If you tape them to one side, it’s not going to move, it’s gonna stay there because there’s only gonna be one page moving. If you have them [page positions] on both sides, they’re [parallel folds] going to be able to move.”

In addition, 57% of students (*n* = 4) who participated in the first interview correctly explained how to build a parallel-fold pop-up that popped up to different heights. For instance, Rosalie explained building tall pop-ups by attaching the page positions closer to the gutter and short pop-ups by attaching the page positions farther from the gutter. These same four students also reported building symmetric parallel folds by attaching the page positions at points equidistant from the gutter and asymmetric parallel folds by attaching the page positions at different points on the left and right pages of the book. Furthermore, 57% of students (*n* = 4, composed of three of the same and one different) noted the distinct left to right motion of parallel folds. However, no students who participated in the first interview reported noticing differences in the magnitude of motion of tall and short parallel folds.

Finally, 29% of students (*n* = 2) reported experiencing trouble making their parallel folds fit correctly inside the book (i.e., the parallel fold protruded out of the book when the book was closed). For example, Violet explained, “At first, I attached it [the parallel fold] all the way over here [indicates page positions far from gutter] and when I closed it, it would stick out of the page [out of the book].” Violet reported fixing this problem by moving her parallel fold’s page positions closer to the gutter, causing her parallel fold to remain inside the book when closed.

Design interview two. In the second interview, students discussed the angle-fold challenges they completed. Unlike in the first interview where a number of students explained basic parallel fold structure, none of the students in the second interview explained that angle folds must span the gutter or that when attached to both pages of the book, angle folds transmit motion. However, 57% of students (n = 4) reported that decreasing the angle of attachment of an angle fold's page positions (i.e., moving the page positions closer to the gutter) caused the angle fold to pop up tall and that increasing the angle of attachment of an angle fold's page positions (i.e., moving the page positions farther from the gutter) caused the angle fold to pop up short. Furthermore, 57% of students (n = 4, three of the same and one different) explained knowing that attaching an angle fold's page positions at the same angle from the gutter (i.e., the same distance) resulted in symmetric angle folds and that attaching an angle fold's page positions at different angles from the gutter (i.e., different distances) resulted in asymmetric angel folds.

In addition, 43% of students (n = 3) identified the up and down or left and right motion of an angle fold, which was similar to the percentage of students who identified directional motion of parallel folds in the first interview. However, one difference between the first and second interviews was that while no students in the first interview reported differences in the magnitude of motion of parallel folds, 71% of the students in the second interview reported that angle folds had different magnitudes of motion. That is, students noticed that depending on the location of the page positions, some angle folds moved more than others when opening the book. Moreover, several students (n = 3) linked the concept of magnitude of motion to structural and functional features such as pop-up height and the location of a pop-up's page positions. For example, Violet explained, "If I wanted to make it [the pop-up] big, I would have to put it closer to the gutter, but when it's big, it doesn't have that much motion."

Finally, whereas in the first interview two students reported experiencing trouble making their parallel folds fit correctly inside their books, no students in the second interview reported experiencing trouble making their angle folds fit correctly inside their books.

Post-instruction design interview. In the post-instruction interview, students discussed their pop-up books. Seventy-seven percent of students (*n* = 10) identified one or more of their pop-ups as a parallel or angle folds. However, just 10% of these students (*n* = 1) explained connecting the pop-up to both sides of the page and 20% of these students (*n* = 2) explained transmission of motion. In addition, 8% of students (*n* = 1) explained building tall or short pop-ups, 38% of students (*n* = 5) explained building symmetric and asymmetric pop-ups, and 38% of students (*n* = 5, four of the same and one different) identified their pop-up's side-to-side or arcing motion. No students explained building pop-ups with different magnitudes of motion.

Finally, 54% of students (*n* = 7) reported experiencing trouble making one or more of their pop-ups fit correctly into the book. Students had several methods for solving this problem. Some students (*n* = 3) reported moving the pop-up's page positions closer to the gutter, some students (*n* = 3) reported cutting off portions of the pop-up that fell outside of the book, and one student reported trimming the size of the strip before reattaching it into the book.

Pre-instruction noticing interviews. Altogether, I recorded 166 coded instances across the eight pre-instruction noticing interviews. Forty-five percent of instances (*n* = 76) referenced objects or colors (e.g., students described characters and background illustrations on the page), 17% (*n* = 28) referenced direction of pop-up motion (e.g., students described side to side movement), 15% (*n* = 25) referenced the degree to which the pop-up extended out of the book (e.g., students perceived some pop-ups as popping out more than others or having more 3-D characteristics), 13% (*n* = 21) referenced pop-up size and complexity (e.g., students recognized multiple pop-ups on a page), and 10% (n = 16) referenced aspects of pop-up structure (e.g., students described how the pop-up was attached to the page).

All students reported noticing objects or colors. For example, when asked to describe the second pop-up in the first paired comparison, Emani explained, “It’s a dog. The dog has spots on it. It has something in its mouth.” Also, 88% of students reported noticing differences in pop-up size and complexity. For instance, Carissa described the second pop-up in the third comparison as “big when you open it.” In addition to noticing objects or colors and differences in pop-up size and complexity, 75% of students reported noticing that pop-ups had directional motion (i.e., the pop-up moved in a particular direction when the book opened or closed). For example, Rosalie noticed that when opened, the pop-ups in the second book in the fourth paired comparison “all went different directions.” Rosalie continued, “Some are going kind of down. Some kind of go up.” Moreover, 63% of students also noticed the degree to which a pop-up extended out of the book. For instance, Jeff explained how the two pop-ups in the third paired comparison were different because, “This one actually pops up toward you and this one’s just flat.”

Finally, 63% of students reported noticing aspects of pop-up structure (i.e., how pop-ups were connected to the page or to each other). For example, when comparing how the pop-ups in the third paired comparison were different, David explained, “This one’s less attached, and this one’s more attached (to the page).” This example demonstrates how when noticing pop-up structure, students did not generally link structural features to how pop-ups worked.

Post-instruction noticing interviews. Altogether, I recorded 183 coded instances across the eight post-instruction noticing interviews. Thirteen percent of instances (n = 24) referenced objects or colors, 18% (n = 33) referenced direction of pop-up motion, 9% (n = 17) referenced the degree to which the pop-up extended out of the book, 6% (n = 10) referenced pop-up size and complexity, and 54% (*n* = 99) referenced aspects of pop-up structure, such as how pop-ups were attached to the page and one another. Considering what individual students noticed, all reported one or more instances of noticing the degree to which a pop-up extended out of the book, the direction of pop-up motion, and aspects of pop-up structure. Finally, 75% of students reported noticing pop-up size and complexity and 63% of students noticed objects or colors.

Students in the post-instruction noticing interview frequently asked to handle the pop-up before explaining any of the attributes they noticed. For many of these students, as soon as they had the pop-up in their hands, they immediately began inspecting how it attached to the page. This resulted in students identifying a variety of structural features they did not notice in the pre-instruction noticing interview, such as the importance of attaching the pop-up to both sides of the page. For example, when examining the first pop-up in the fourth paired comparison, Rosalie explained, "Without this side (left side of the book), it wouldn't be able to pop-up because you have to have the page positions attached to both sides of the gutter." Similarly, when inspecting the second pop-up in the first paired comparison (contrasting page positions of parallel folds), Emani pointed out that the pop-up's page positions were on either side of the gutter and that opening and closing the book "pulled" the pop-up, resulting in the pop-up moving from side to side. In this instance, Emani identified the structural feature that allows a pop-up to transmit motion, the pop-up must span the gutter and attach to the left and right sides of the page.

A number of students also reported noticing structural differences between parallel- and angle-fold pop-ups. For example, when examining the first pop-up in the second paired comparison, Rosalie explained, "It's an angle fold, since it's angled (gestures a triangle). What makes it angled is the lines intersect (gestures intersecting page positions). And then on parallel (gestures parallel page positions), they never intersect." In this example, Rosalie used talk and gesture to illustrate the main differences between parallel- and angle-fold pop-ups, the orientation of their page positions to the gutter.

In addition, several students noticed visual differences between symmetric and asymmetric pop-ups. For example, when describing what he noticed about the first pop-up in the first paired comparison, Mario explained, “It’s a parallel fold, and it’s symmetrical.” When asked to explain how he knew the pop-up was symmetrical, Mario answered, “If you cut it in half, it looks the same on both sides, and if you cut it in half and it’s not the same, it’s asymmetrical.” Here, Mario explained his technique for identifying symmetric and asymmetric pop-ups. He imagined a line down the gutter, and if the line split the pop-up into even parts, the pop-up was symmetric, but if the line split the pop-up into uneven parts, the pop-up was asymmetric.

Finally, inspecting the commercial pop-ups in the paired comparisons prompted some students to explain how to build tall and short pop-ups. For example, when examining the second pop-up from the second paired comparison, Jorge explained, “It’s a parallel fold. It’s symmetrical, and it pops up a lot. Whenever you put the page positions closer (to the gutter), it makes it real tall. Whenever you separate it, it makes it real short.” In this instance, Jorge explained understanding an important structural feature of pop-ups, adjusting the distance from the page positions to the gutter changes a parallel-fold pop-up’s height.

Summary: Noticing interviews. Table 3 displays the proportion of coded instances for the pre- and post-instruction noticing interviews. Coding categories included: OC (i.e., objects or colors), DM (i.e., direction of pop-up motion), EOB (i.e., the degree to which the pop-up extended out of the book), SC (i.e., pop-up size and complexity), and PUS (i.e., pop-up structure). To summarize, analysis of pre- and post-instruction noticing interviews indicated that prior to paper engineering instruction, students frequently noticed objects and colors, such as characters and background artwork, but infrequently noticed attributes of pop-up structure.

Table 3

Pre- and Post-instruction noticing interview summary

	Coding category				
Interview	OC	DM	EOB	SC	PUS
Pre	45	17	15	13	10
Post	13	18	9	6	54

Note. Numbers represent proportions of the total coded instances for each interview.

However, after paper engineering instruction, students noticed structural features of pop-ups far more frequently. In addition, students' talk and gesture demonstrated that students linked what they noticed about pop-up structure to what they learned about pop-up function during instruction. In the next section, I illustrate further how students had opportunities to link ideas about pop-up structure and function by troubleshooting design challenges.

Part III: How Does Participating in the Practice of Troubleshooting Contribute to Students Learning About Pop-Up Structure and Function?

Participating in the practice of troubleshooting promoted students learning about how pop-ups: (a) attached to the page, (b) moved in different directions along different axes, (c) stayed inside the book when closed, (d) popped up tall or short, (e) popped up symmetric or asymmetric, and (f) moved with different magnitudes of motion. The three instances that illustrate aspects of what students learned are described below.

Instance 1: Introducing troubleshooting by reverse engineering. Early in instruction students reverse engineered a pop-up from a commercial book into a transparent book. Troubleshooting the problems they faced during this design challenge prompted some students to recognize the effects of attaching pop-ups onto the page in specific ways. For example, when I asked the class to describe some of the problems they encountered, Mario explained that he and his group discovered needing to attach their angle-fold pop-up's page positions to specific locations on the transparent book in order for it to function correctly (see transcript below).

Mario: The folds [page positions] need to be in specific locations.

Mr. R: Can you tell us a little bit about what you mean?

Mario: You have to separate them [the page positions] a little bit from the gutter.

Mr. R: What happens if you put them too close to the gutter?

Mario: They won't fold right.

After hearing from Mario, I asked the students if they experienced any other problems while reverse engineering their commercial pop-ups and if they learned something about how their pop-ups worked in the process. Like Mario, Kara explained noticing a relationship between the angle-fold pop-up's page positions and how well it worked.

Kara: How to place the pop-ups in the correct place so they can open correctly.

Mr. R: Tell me a little bit more about that.

Kara: If you put the pop-up too close to the gutter, the pop-up won't pop-up correctly. And if you put it [into the book] correctly, it will pop-up correctly.

Mario and Kara's responses were indicative of the way students tended to explain what they noticed about pop-up behavior in the reverse engineering design challenge. That is, early on, students generally found it difficult to describe the problems they experienced and to explain exactly what they did to make their pop-ups work correctly. In this instance, Mario and Kara, who were in the same group, did not have the language to fully explain that when reverse engineering the angle-fold pop-up, they attached it into the transparent book at too steep an angle to the gutter, causing it to rise off the page to an incorrect height and prevented the book from closing completely (Figure 8, left side). Mario and Kara also were unable to fully explain that they troubleshot this problem by increasing the angle at which the pop-up's page positions were attached to the gutter (Figure 8, right side). Doing this allowed the pop-up to rise up off the page to the correct height and allowed the book to open correctly.

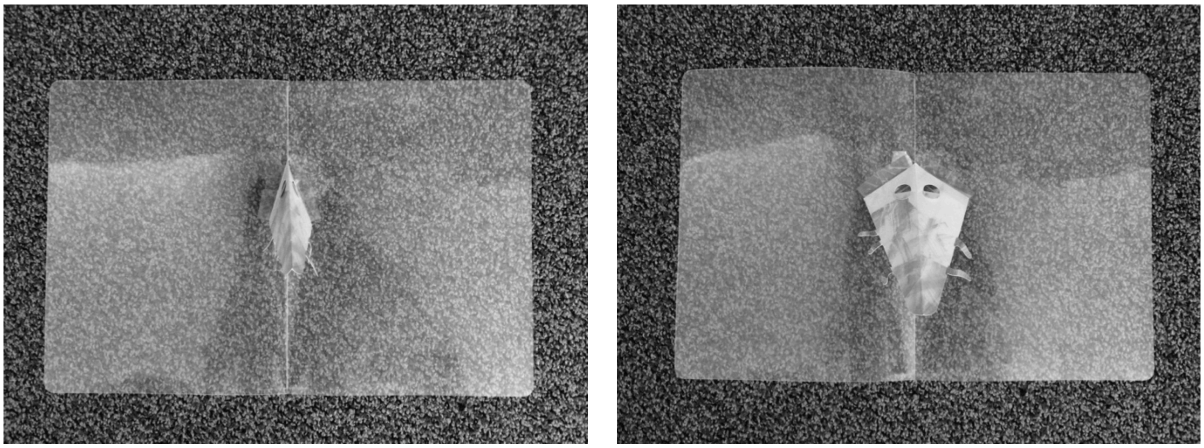


Figure 8. A) Angle-fold pop-up attached at a steep angle to the gutter preventing the book from closing correctly. B) Angle-fold pop-up attached at a wider angle to the gutter.

Next, after Mario and Kara shared, Janice reported initially attaching the parallel-fold pop-up to one side of the transparent book rather than to both sides. As a result, when she closed her book, the cover crushed her pop-up. This experience prompted Janice to explain, "I learned that some part of the pop-up has to be in the crease or that something has to be in the middle so that it will pop-up." In other words, attaching her pop-up on one side of the page helped Janice understand that the pop-up must span the gutter. To solve this problem, Janice reported altering her pop-up by attaching its page positions to each side of the book.

Finally, Emani explained how her group experienced a problem with the way they attached their parallel-fold pop-up into the transparent book and its resulting movement. Emani noticed, "it [the transparent book] would open but the tail wouldn't move." When I asked Emani how she fixed the problem, Emani answered, "we stretched it [the left page position] a little more to the left." Here, Emani, explained that she and her group members troubleshot the problem by adjusting the distance of the left page position farther from the gutter.

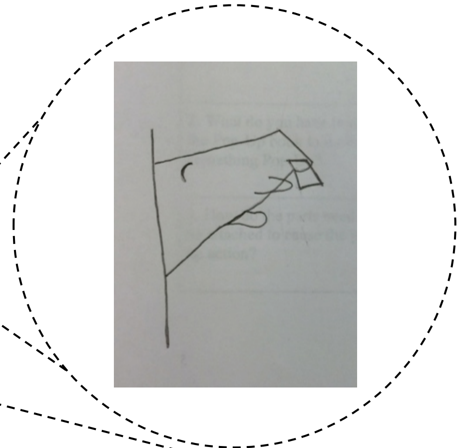
In each of these examples, students reported troubleshooting problems they experienced when reverse engineering commercial pop-ups by adjusting their pop-up's page positions in relation to the gutter. Even though students did not always use paper-engineering terminology to describe the problems they experienced or to explain how they troubleshot those problems, students reported learning about how attachment points influenced the way pop-ups worked.

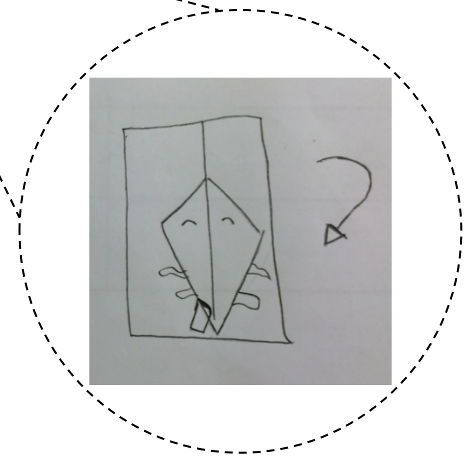
In addition to helping students recognize the effect on pop-up function of attaching pop-ups to different page positions, troubleshooting the problems they encountered during the reverse engineering design challenge also promoted students noticing pop-up attributes such as directional motion along different axes. For example, when I asked the class if they noticed anything about how their pop-ups moved, Jorge, whose group reverse engineered the parallel-fold dog pop-up, explained, "when you open the book, the tail will move to the left. And when you close it, it will move back to the right." On the other hand, Kara, whose group reverse engineered the angle-fold beak pop-up, used drawings to show how her group's pop-up moved in an arc down and towards the middle of the page (see transcript and figures below).

Kara: My awesome bird drawing is right there.

Ms. C: OK. So tell us what that shows.

Kara: Well, this shows where it [the beak]
was at when it [the book] was closed.
But when you opened it [the book],
the beak would come down
into the middle.





Mr. R: So what is this arrow showing me?

Kara: The arrow's showing you how it moves.
It would start from right there
then it moved down
(traces arrow with finger).

This example demonstrates that while troubleshooting how to attach the commercial pop-ups into the transparent books, some students found that parallel and angle folds moved in slightly different ways. While Jorge explained that the parallel-fold dog pop-up moved from right to left along the X-axis, which is a characteristic of parallel fold motion, Kara explained that the angle-fold beak pop-up moved from right to left on the X-axis, but also arced from top to bottom along the Y-axis, which is a characteristic of angle fold motion. Thus, even though students may not have yet developed an extensive paper engineering vocabulary, troubleshooting promoted students noticing that different types of pop-ups moved along different axes.

Instance 2: Troubleshooting parallel-fold design challenges. In addition to reverse engineering, early in instruction students participated in several parallel-fold design challenges. Troubleshooting the problems they faced when building parallel folds prompted students to develop heuristics for: (a) making pop-ups stay inside the book when closed, (b) altering pop-ups so that they popped up tall or short, and (c) altering pop-ups so that they popped up symmetrically or asymmetrically.

The first problem many students faced when building parallel folds was that sometimes, after attaching a cardstock strip into the transparent book, closing the book caused the strip to protrude out of the book. For example, after I asked for volunteers to share about some of the problems or issues they experienced when making parallel folds, Kara explained that when she taped her cardstock strip symmetrically to page positions on either side of the book, her pop-up stuck out of the book when it was closed (see transcript below).

Kara: Well, my first issue was I taped it [the strip] down on the line around five [at the five centimeter mark] and it [the strip] came out too far when I closed it [the book]. So then I changed it and I moved the end of it [the page position] to four.

Mr. R: So tell me in paper engineering terms, what did you do? We have terms like page position, we have terms like gutter. As a paper engineer, what did you do?

Kara: OK. Well, I got my page position. I taped it to the line four.

Mr. R: And, is it towards the gutter or farther away from the gutter?

Kara: Towards the gutter.

Mr. R: OK. So, this is what I'm hearing. I'm hearing that it [the strip] was out of the book and you troubleshot by moving the page position closer to the gutter.

In this instance, Kara reported troubleshooting the problem she experienced by moving her pop-up’s page positions from the five-centimeter mark to the four-centimeter mark. In doing so, Kara demonstrated using a heuristic for making protruding pop-ups fit correctly into the book when closed (i.e., move the pop-up’s page positions towards the gutter).

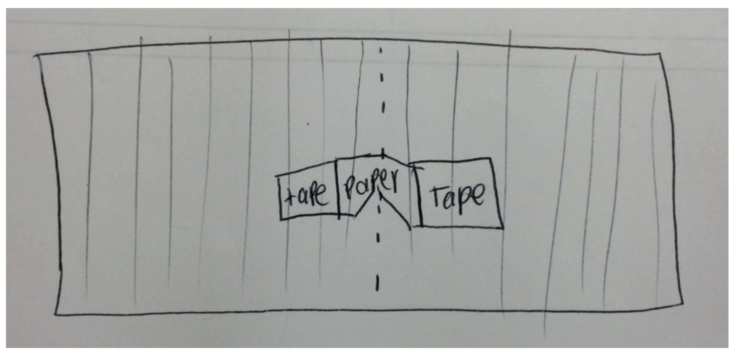
The second problem many students faced when building parallel folds was how to make them pop up very tall or very short. Several students troubleshot this problem using trial and error. That is, they attached their cardstock strips symmetrically at varying distances from the gutter, closed and opened the book, assessed how high the parallel fold appeared to pop up, and then repeated the process after repositioning the strip's page positions. However, most students searched for a pattern. Violet used a picture she drew to share the pattern she found with the class. The transcript of the episode, along with Violet's picture, appears in the excerpt below.

Violet: When it's [the strip is] closer to the gutter, it pops out more. It gets taller. But farther away, it stays flat. So I drew a picture of it being closer to the thing.

Mr. R: Closer to the thing?

Violet: Closer to the gutter.

Mr. R: OK. So we have a couple things going on, right?



Here's your picture. This is your strip of paper [gestures to drawing]. Based on what you're telling me, is this one [parallel fold] going to be high or low?

Violet: It's going to be high.

Mr. R: OK. And if you wanted to make it low, what would you do?

Violet: You would stick it [the page positions] farther away from the gutter.

In this instance, Violet illustrated how she made tall and short pop-ups by displaying a drawing of a parallel fold with page positions attached near the gutter. Violet explained that the parallel fold in her drawing would pop up high, but that moving the page positions farther away from the gutter would cause the parallel fold to pop up short. In this example, Violet demonstrated using a heuristic to make tall pop-ups (i.e., attach the page positions nearer to the gutter) and short pop-ups (i.e., attach the page positions farther from the gutter).

The third problem many students faced when building parallel folds was how to make them pop up symmetrically (i.e., with the fold over the gutter) and asymmetrically (i.e., with the fold on the left or right side of the gutter). For example, when building her first parallel fold, Abby reported that instead of popping up symmetrically, her fold appeared lopsided.

Abby: It [the parallel fold] was lopsided when I taped it in.

Ms. C: It was lopsided? Explain what that means.

Abby: When I opened it [the book], it [the parallel fold] was like [gestures to the side].

Ms. C: So instead of sticking straight up, it was going to the side a little? OK. So how'd you fix that?

Abby: I moved the page positions.

Mr. R: And how did you move them? Where did you put them to fix it?

Abby: I put them on the same line.

Ms. C: What do you mean the same line?

Abby: On number three [the three centimeter mark] on this side [left side] and number three [the three centimeter mark] on the other side [right side].

In this instance, Abby reported troubleshooting her lopsided parallel fold by attaching its page positions at exactly the same distance from the gutter on either side of the book, thereby making a symmetric parallel fold. After Abby shared, I asked for a volunteer to explain the relationship between symmetric and asymmetric parallel folds. Violet summarized, “It's [the parallel fold is] symmetrical when the paper is folded in half and one page position [is] on one side and the other one’s on the other, but they're on the same mark. But it's asymmetric when one side [page position] is farther away from the gutter and the other is closer away." With this explanation, Violet showed she had developed a heuristic for making symmetric parallel folds (i.e., attach the page positions to the same place on either side of the page) and asymmetric parallel folds (i.e., attach the page positions to different places on either side of the page).

Instance 3: Troubleshooting angle-fold design challenges. In addition to parallel-fold design challenges, later in instruction students participated in several angle-fold design challenges. Troubleshooting the problems they faced when building angle folds prompted students to use some of the same heuristics they developed to solve the problems they encountered when building parallel folds. For example, when I asked the students to share how they made an angle fold that popped up very tall, Janice explained that she did not have any issues nor did she need to troubleshoot because she recalled what she did to make tall parallel folds (see transcript below).

Janice: I didn't have any issues and I didn't have any troubleshooting. I knew what to do because I remembered the advice that we did in the couple of last weeks. The close[r] it [the page positions] will be to the middle, the higher it [the pop-up] will be. And the farther it [the page positions] is to the middle, the flatter it [the pop-up] will be. So I just decided to put it [the page positions] on the number one. Number one is the closest one [the closest line to the gutter] (Figure 9).

Ms. C: OK. Janice, how did you know to do that?

Janice: Because I know that the closer it [the page positions] would be to the middle, then the higher it [the pop-up] would be.

Ms. C: How'd you know that though?

Janice: Because the last time [when building parallel folds], we were doing the tallest it could be [using] the little strip [the parallel fold].

Ms. C: OK. So when we were doing the parallel folds, and we did the maximum [height], did you have to do the same thing or a different thing?

Janice: The same thing cause you have to put it [the page positions] on the same number, so I just put it on [the one centimeter mark] and that was really high.

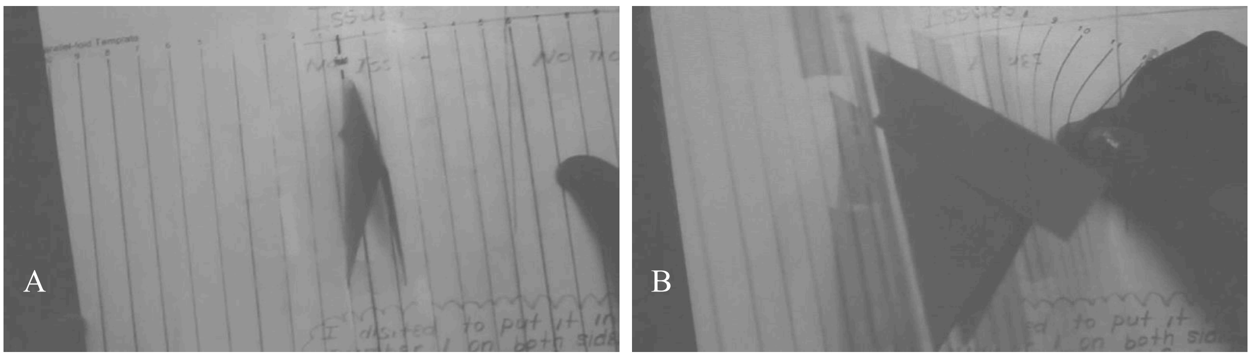


Figure 9. A) Janice reported making her angle fold tall by attaching the page positions to the closest line to the gutter, the one-centimeter mark. B) Side view of Janice's tall angle fold.

Like Janice, Abby employed a heuristic she learned when troubleshooting parallel-fold pop-ups to make her asymmetric angle-fold pop-ups. Abby explained, "I just moved this [the left page position] over to this side [the left side] and then taped it more on this side to make it go to that side [the left side]." Here, Abby reported making an asymmetric angle fold by attaching one page position close to the gutter and the other far from the gutter, which was identical to the heuristics students developed earlier in instruction for making asymmetric parallel folds.

In addition to employing familiar heuristics to solve problems when building angle folds, some students also reported that troubleshooting problems when building angle folds helped them identify differences in the magnitude of angle-fold pop-up motion. For example, Calvin noted that when his angle fold's page positions were attached close to the gutter, his pop-up moved very little when he opened and closed the book, but that when his angle fold's page positions were attached farther from the gutter, his pop-up to moved much more.

Mr. R: So is there anything else you noticed about yours, Calvin?

Calvin: I noticed whenever I close it [the book], the shape [of the pop-up] doesn't change as much. It just barely moves.

Mr. R: It barely moves you said?

Calvin: The more I put it [the page positions] out, the more it [the pop-up] would actually start moving.

Mr. R: Say that again.

Calvin: The closer I move the page positions out [gestures moving the page positions away from the gutter], the more it [the pop-up] would move.

In this instance, while exploring how to make tall angle fold-pop-ups, Calvin discovered that attaching angle folds at different distances from the gutter influenced how they moved upon opening and closing the book. Specifically, Calvin found that angle folds attached near the gutter had less magnitude of motion than angle folds attached far from the gutter.

Discussion

This study was motivated by a number of reports indicating the potential of integrated STEM education to promote students learning concepts spanning STEM disciplines (Honey et al., 2014; Katehi, et al., 2009; NRC, 2010) and by the recent emphasis on shared disciplinary practices in K-12 science and engineering education (Achieve Inc., 2013; NRC, 2012). Specifically, I examined: (a) how students engaged in engineering design by building paper pop-up books, (b) what students understood about pop-up structure and function, and (c) how participating in the practice of troubleshooting helped students learn about their pop-ups.

What is the Nature of the Pop-Ups Students Build and What do Students' Designs Indicate about Paper Engineering as a Medium for Self-Expression?

Results suggest that authoring pop-up books supported narrative expression. Many students drew on their personal lives, or their experiences in related digital realms, to write complex stories and create unique characters. Moreover, pop-up books served as vehicles for self-expression in which students had the freedom to incorporate aesthetically pleasing elements based on their own unique interests. This was exemplified in the two case studies. In the first, Janice demonstrated favoring one type of fold over another and designing pop-ups based on the type of action she wanted to achieve on a particular page. In the second, Alvin demonstrated that for him, pop-up structure came second to achieving a good story, and that aesthetic features, such as the size of his bear, were more important than pop-up action. Because paper engineering allowed students to design with aesthetic and functional goals in mind, in the future, it might prove a productive context in which to study the interplay between practice and self-expression, such as how students trade off between functional and aesthetic decisions.

Results also showed that students attached multiple pop-ups in parallel on the same page, but did not attach multiple pop-ups in series. Hence, students tended to make more pop-ups rather than more complex pop-ups. In the future, altering paper-engineering instruction so that students have the opportunity to build compound pop-ups by connecting parallel- and angle-fold pop-ups together in series may promote students building more complex pop-ups. Unfortunately, because of time limitations, we were unable to develop this during instruction, and as a result, students had fewer opportunities to increase the complexity of their pop-ups.

For several students, insufficient time prevented them from finishing their pop-up books before the end of instruction. Although we expected students would spend a great deal of time authoring their stories, it quickly became clear that students would benefit from additional time. Allotting more time for planning, developing, and writing stories might also help facilitate making stronger connections between paper engineering and critical school subjects such as reading and writing. As it stands, although our results indicated that authoring pop-up books supported narrative exposition, we did not have an explicit plan in place to maximize the potential connections between paper engineering and literacy instruction. A comparison of students' efforts to develop narrative expression in the paper engineering context with more traditional efforts in literacy instruction, such as writing essays, might inform future efforts to incorporate multiple media and modes into literacy education.

What do Students Understand about Pop-Up Structure and Function?

Results of the design and post-instruction design interview analysis indicated that students who built pop-ups described structure-function relationships less frequently than we anticipated they might. This was especially true for the post-instruction design interviews in which students answered questions about their pop-up books. One explanation for this is that the interview questions did a poor job of eliciting information about pop-up structure and function. To gain more insight into what students know about pop-up structure and function, it seems important to refine the interview questions so that they prompt students to discuss structure and function more fully. A second explanation for why students described structure-function relationships less frequently than we anticipated is that designing instruction around authoring a story prompted students to explain more about their stories and less about how their pop-ups worked. In future iterations, it will be important to strike a balance between allowing students to report about the content of their story and to report about pop-up structure and function.

When students did explain pop-up structure and function, they tended to focus on different elements in each of the three interviews. For example, in the first interview, students were more apt to explain how to attach pop-ups to the page than they were in the second or third interviews. This may have been because by the second interview, students understood how to make pop-ups and did not find it necessary to explain how to attach them to the page. Similarly, in the first interview, no students reported noticing magnitude of motion after completing the parallel-fold design challenges. However, during the second interview, after completing the angle-fold design challenges, a number of students reported noticing magnitude of motion. Hence, it appears that working with a particular type of fold (i.e., an angle fold) helped students discover specific attributes of pop-up function (i.e., the magnitude of pop-up motion).

However, in contrast to the more limited exposition of structure-function in the design interviews, asking students what they noticed about contrasting cases of pop-up designs before and after instruction suggested striking changes. There was a significant difference between what students reported noticing about pop-up structure and function prior to instruction compared to what they reported noticing about pop-up structure and function after instruction. Namely, students shifted from describing readily recognizable objects or colors to describing details of pop-up structure, such as how pop-ups attached to the page, and the resultant pop-up function.

Finally, results indicated opportunities for satisficing (i.e., finding a sufficient but not optimal solution to a problem) might have affected how deeply students needed to reason about structure and function when building pop-ups. For instance, in the post-instruction design interview, several students reported that their pop-ups did not fit in the book correctly; they protruded out of the book. Rather than fix this problem by adjusting the page positions, some students simply used scissors to trim off parts of their pop-ups. These students demonstrated satisficing in lieu of applying their knowledge of pop-up structure and function to solve the problem. Opportunities to satisfice represent a formidable obstacle to overcome when developing learning environments geared at engaging students with particular content. Where opportunities for satisficing exist, there is potential for students to inadvertently undercut instructional goals.

How Does Participating in the Practice of Troubleshooting Contribute to Students Learning about Pop-Up Structure and Function?

Organizing paper engineering instruction around design challenges promoted students participating in the practice of troubleshooting and learning about aspects of pop-up behavior such as: (a) attachment to the page, (b) direction and magnitude of motion, (c) height, and (d) symmetry. However, many students reported developing heuristic-based knowledge to solve the problems they encountered when building pop-up books, illustrating that to build their pop-ups, students depended on practical forms of knowledge rather than established types of knowledge that focus on formal calculations and canonical explanations (Azevedo, 2013).

The drawback of this finding is that although developing heuristic-based knowledge helped students account for generalizable relationships within the pop-up system, it did not ensure students optimizing their pop-ups or reasoning deeply about their underlying structure. Take for example, Kara, who developed a helpful heuristic to prevent her parallel-fold pop-up from protruding out of the book. Did Kara learn as much as she could have? Perhaps not. Let us consider why. Figure 10 highlights the underlying mathematical relationship governing if pop-ups protrude out of the book. The figure depicts an asymmetric parallel fold attached to the page of a book. When the book is closed, the distance A + B = C + D. (This is true of all parallel folds.) If the distance A + B is more than the distance from the gutter to the edge of the book, the pop-up will protrude out of the book. Notice that in Figure 10, the distance A + B is larger than the distance from the gutter to the edge of the right side of the book. Hence, closing the book in the figure will cause the pop-up to protrude out of the book.

Thinking back to Kara, we now know that although she developed a reliable method to prevent her pop-ups protruding out of the book, and learned something about pop-ups in the process, in this case, developing a heuristic resulted in her sidestepping an important relationship governing how pop-ups work. Using a heuristic meant Kara did not need to reason deeply about the pop-up system. As a result, Kara did not gain a deep understanding of the pop-up system.

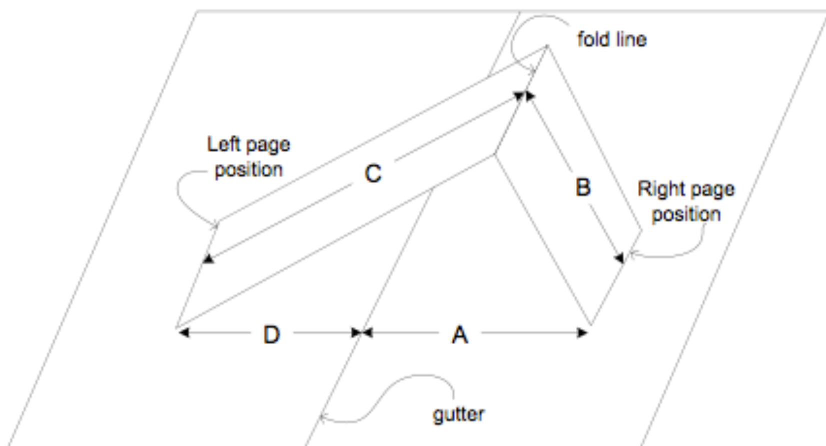


Figure 10. If the distance A + B is greater than the distance from the gutter to the edge of the book, the pop-up will protrude out of the book (adapted from Benenson & Neujahr, 2009).

In order for students to better learn about how simple mechanical systems work through troubleshooting, it is critical to organize instruction so that they design and build artifacts based on a deep and consequential understanding of the system. Curricular tasks must compel students to troubleshoot in particular ways and in a particular sequence. Otherwise, there is a very real possibility students will troubleshoot their way out of learning the intended content.

One way to combat this would be to redesign the curriculum to highlight the underlying mathematical relationships within pop-up books that are consequential to students when building and troubleshooting pop-ups. For example, giving students a challenge that cannot be solved with a heuristic, such as making the pop-up rise off the page to a very specific height, might push children to probe the underlying relationships governing pop-up structure and function.

Implications

As demonstrated here, orchestrating an engineering design program is a complicated endeavor. There are several obstacles standing in the way of accomplishing this type of work. One is that many teachers are accountable for preparing their students for high-stakes end-of-year assessments, they typically only have a finite amount of time they can dedicate to engineering design programs. When teachers make time for engineering design programs, a new question arises: What is the correct class in which to enact the program? The current divisions in the school day make it difficult to know where to situate engineering design programs. Should they be performed in math class, as this project was, or should they be performed in science class? Unfortunately, the likelihood that engineering design program will be performed in an engineering class is low because there are relatively few dedicated K-12 engineering classes and perhaps even fewer trained and certified engineering educators to teach those classes.

When teachers do dedicate time to engineering design programs, it is important to include them in as many facets of the program as possible. Partnering with teachers promotes them taking an active role in the implementation of the engineering design program and also helps teachers and researchers tailor instructional content and instructional styles to meet students' needs. In other words, engineering design programs stand a better chance of being meaningful and durable when teachers are involved and invested in the success of the program.

In addition to partnering with classroom teachers, it is also important to develop engineering design programs based on activities that students can enter into relatively easily and that have a high ceiling for what students can do and learn. Easy entrée appeals to a range of students and promote sustained motivation for students to participate in the project over time. High ceiling programs ensure that a range of students can work productively, and perhaps at different rates to design and build artifacts while participating in meaningful aspects of engineering design. Furthermore, it is important for students to design with a particular audience in mind. Designing with an audience in mind parallels how professional engineers design in the outside world. Engineers must reflect on their designs to determine if they fit a client's needs. Designing for an audience promotes K-12 students experiencing and understanding this mindset. Finally, it is important to anchor engineering design programs in culturally accessible memes and content that students enjoy. This allows students to connect to their personal lives and with their classmates when designing, providing a source of motivation and creativity.

More specifically, regarding the development of engineering design programs meant to engage students in engineering practices to learn content that spans science and engineering, I recommend orchestrating learning environments in which students can participate in ensembles of practice, as is common in professional engineering. In particular, reverse engineering appears to be a springboard practice that engages students in various other practices. For example, in this study, I found that as students participated in reverse engineering they experienced structural and functional problems, which in turn led them to troubleshooting different aspects of their pop-ups. Thus, designing instruction around reverse engineering promoted troubleshooting, which in turn promoted students learning about structure and function.

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Appendix A

Pre-Instruction Paired Comparison Interview

Comparison	Book A	Book B	What the comparison highlighted
1	*Let's Make It Pop-Up* Symmetric parallel fold. (Butterfly)	*Snappy Little Colors* Asymmetric parallel fold. (Dog)	Similarities and differences between the page positions and the motion of symmetric and asymmetric parallel-fold pop-ups.
2	*Let's Make It Pop-Up* Symmetric parallel fold. Medium height. Medium motion. (Box)	*Wide-Mouthed Frog* Symmetric angle fold. Medium height. Medium motion. (Bird)	Similarities and differences between page positions, directional motion, range of motion, and height of symmetric parallel-fold and symmetric angle-fold pop-ups.
3	*Wide-Mouthed Frog* Two symmetric angle folds. High height. Low motion. (Alligator)	*Giant Pop-Out Shapes* Two symmetric angle folds. Low height. High motion. (Heart)	Similarities and differences between the page positions and the range of motion of angle-fold pop-ups opening to different heights.
4	*How Many Bugs in a Box?* Three symmetric parallel folds (Butterflies)	*Snow Bugs* Three asymmetric angle folds (Snowballs)	Similarities and differences between the page positions and the directional motion of multiple symmetric and asymmetric parallel and angle folds on the same page.
5	*Snappy Little Colors* Two angle folds connected in series. (Crab)	*Snappy Little Colors* One angle and one parallel fold connected in parallel. (Mole)	Similarities and difference between the page positions and the directional motion of combinations of parallel and angle folds on the same page.

Appendix B

Range of Student Pop-Up Book Topics

Student	Book title	Topic
Abby	Animals	Exotic animals in their habitats
Adnan	Soccer Stars	Professional soccer players
Alicia	The Lovely Unicorn	A unicorn and other animals
Alvin	The Wizard Killer	A wizard and his magic
Ariel	Titanic Se Unde	Sinking of the Titanic
Calvin	(No title)	A pair of traveling pants
Carissa	Earth's seasons	The four seasons
Cedric	Sports	Different sports
Ciara	Spring	Spring sights
Dana	It	Life
David	(No title)	A caterpillar turning into a butterfly
Emani	Love in the Arctic	Arctic animals in love
Everett	Aliens	A family of aliens
Gwen	The Life of a Cheerleader	Gwen's life as a cheerleader
Janice	The Girl that Never Gave Up	Janice's experience with bullying
Jeff	The Adventures of Taco	A taco on an adventure
Jorge	(No title)	Nyan Cat fights Tac Nyan
Kara	Chulo, the Big and the Brave	Kara's pet dog meets other animals
Karen	Jimmy Jet and His TV Set	Effect of watching too much TV
Kiyara	Sports of the World	Sports
Leah	Sunny Summer	Summer activities
Leslie	My Best Friend	Friendship
Mario	The Haunting	Horror stories
Oscar	Ninja	Graffiti images
Rosalie	The Adventures of Maximus and Pascal	Friends on an adventure
Sarah	The Unicorn	A unicorn and other animals
Violet	How to Celebrate My Party	A young girl's birthday
Zeb	A Weird Day of Friday	Zeb hanging out with his friends

Appendix C

Coding Scheme for Design and Post-Instruction Design Interviews

Category		Description	Example
Structure and Function	Basic Structure (BS)	*General:* Student explains that his or her pop-up's page positions are attached to both sides of the gutter *OR* student correctly identifies his or her pop-up as a parallel or angle fold. *For a parallel fold:* Student explains that parallel folds are attached to the page at points parallel to the gutter. *For an angle fold:* Student explains that angle folds are attached to the page at points at an angle to the gutter.	**Example 1:** "We had to have the page positions on both sides of the gutter." **Example 2:** "At first I didn't know how to make them pop-up. I figured out if we tape them onto each side of the page position, then they'll pop-up better than if you tape them to one side." **Example 3:** "This one was an angle fold."
	Pop-Up Height (PUH)	*General:* Student explains that changing the location of the page positions in relation to the gutter causes the height of the pop-up to change. *For a tall pop-up:* Student explains that moving the page positions closer to the gutter will cause the pop-up to become taller. *For a short pop-up:* Student explains that moving the page positions away from the gutter will cause the pop-up to become shorter.	**Example 1:** "You make the tallest one by trying to make the ... page positions taped to both sides as close to the gutter as you can." **Example 2:** "To make a low pop-up, like this one, put the page positions farther away from the gutter."

Category		Description	Example
	Keeping the Pop-Up in the Book (ITB)	*For a parallel fold:* Student explains that moving the page positions closer to the gutter prevents the pop-up from protruding out of the book. *For an angle fold:* Student explains repositioning the fold by moving the pop-up up or down the gutter to keep an angle fold from going outside of the book. *Note:* Student may explain trimming the strip or adjusting the length of the strip some other way.	**Example 1:** "There was an issue... It would stick out, so we had to spread it out some more." **Example 2:** "It was too high so the beak would be coming out of the book. I had to move it into the middle." **Example 3:** "Mario cut this [the strip] shorter."
	Symmetric vs. Asymmetric (SA)	*General:* Student explains that symmetric pop-ups fold over the gutter and that asymmetric pop-ups fold to the right or left of the gutter *OR* student correctly identifies his or her pop-up as symmetric or asymmetric. *For a symmetric pop-up:* Student explains that attaching the pop-up at page positions equidistant from the gutter will form a symmetric pop-up. *For an asymmetric pop-up:* Student explains that attaching the pop-up at page positions not equidistant from the gutter will form an asymmetric pop-up.	**Example 1:** "If I moved one [page position] closer or farther away from the gutter, and one [page position] was the same, it would be asymmetrical." **Example 2:** "It was symmetrical and I wanted to make it asymmetrical, so I just moved it [one page position] from there to here [closer to the gutter] so it can be closer to the gutter."
	Direction of Motion (DM)	*For a parallel fold:* Student describes or gestures the pop-up as moving from right to left. *For an angle fold:* Student describes or gestures the pop-up as moving right to left or up and down.	**Example 1:** "It would move from right to left, and when you close it, from left to right." **Example 2:** "When you close it, the pop-up goes in to the right and if you open it, it goes to the left."

Category		Description	Example
	Magnitude of Motion (MM)	*General:* Student relates pop-up motion to a pop-up's page positions. *For a tall pop-up:* Student explains that taller pop-ups have less motion because the page positions are attached closer to the gutter *For a short pop-up:* Student explains that shorter pop-ups have more motion because the page positions are attached farther from the gutter. *Note:* Student may demonstrate MM by attaching a post it note flag to a pop-up or by gesturing pop-up motion while opening and closing the book.	**Example 1:** "If it's [the page position] closer together, it doesn't have much movement." **Example 2:** "To make it tall you will have to put the page positions closer to the gutter, but there will be less motion whenever it's closer"