# Engaging in Design: Reflections of Young Paper Engineers

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**Abstract:** Despite a recent push to expand the scope of P-12 engineering education, research on how young children understand and engage in the core practice of engineering design remains scarce. In order to investigate how young children engaged in engineering design, we presented 31 children (ages 8-9) from two third-grade classrooms with the task of constructing a pop-up book, (also called paper engineering). Here we report the results of a qualitative analysis of 29 children's semi-structured interviews in which they answered questions about their pop-up books post-construction. We found that children used troubleshooting and satisficing (among other techniques) to solve problems they experienced while constructing pop-up books. This research has implications for elementary grade engineering design instruction. In particular, it highlights the need to promote activity structures that foster a normative practice of troubleshooting.

## Introduction

Recently, there has been an effort to expand P-12 engineering education in the U.S. (Brophy, Klein, Portsmore & Rogers, 2008). Proponents of the expansion claim that in addition to improving children's learning and achievement in science, technology, and math, increased emphasis on engineering education has the potential to improve children's (a) awareness of engineering and the work of engineers, (b) understanding of and ability to engage in engineering design, (c) interest in pursuing engineering as a career, and (d) technological literacy (Katehi, Pearson, & Feder, 2009, pp. 49-50). Because empirical evidence supporting these claims is sparse, there have been calls for increased research into P-12 engineering education, and in particular, engineering design.

Engineering design is the purposeful, systematic, iterative, and social process that engineers use to solve problems (Katehi et al., 2009). The fundamental aspect of engineering setting it apart from other subjects is its focus on design (Dym, Agogino, Eris, Frey, & Leifer, 2005). In this paper, we report on a study that examined how children solved problems while participating in an engineering design activity. In doing so, we aim to add to the existing literature about how children understand and engage in engineering design.

## Paper Engineering

We chose to examine the way elementary age children engaged in engineering design by piloting an instructional unit where they created a pop-up book—an activity known as paper engineering. Paper engineering aims to transition young learners from craft-based activities, where design goals tend to focus on aesthetics and trial-and-error construction, to engineering design, where design goals are subject to more analytic decisions (Hendrix & Eisenberg, 2005). Paper engineering approximates engineering activity in several ways. First, paper engineering presents an ill-structured environment, so that children must make decisions in light of uncertainty about how to construct working pop-up books. Each of these decisions can generate situations where children are required to decompose systems, generate and test solutions, analyze and evaluate results, and optimize their books. Second, design of pop-up books often demand trade-off's among elements of design, such as the amount of pop-up motion, the height of the pop-up off the page, the location of the pop-up inside the book, and material constraints, such as the rigidity of the paper. Third, children produce sketches and prototypes (much like professional engineers do) to describe structural and functional relationships within their pop-up books. Finally, children work in groups to complete cycles of design and redesign where their results are subject to public scrutiny and where sharing information spurs revision and innovation.

There are many different types of pop-ups that children can and do make. Here, we give background on only the type (parallel-fold) that will allow readers to follow the distinctions made in the findings section of this paper. 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 blank book (Figure 1, left). He or she tapes the strip so that both attachment points (called *page positions*) are *parallel* to the center of the book (called the *gutter*) and aligned with each other. After attaching the strip, the paper engineer closes the book. Because the strip is attached to both sides of the book, it pushes outwards and folds as the book is closed. The right side of Figure 1 shows how the strip looks when the book is reopened. Parallel-folds can be symmetric or asymmetric. Symmetric parallel-folds are attached at page positions equidistant from the gutter and fold in the middle of the strip. The parallel-fold in figure one is an example of an asymmetric parallel-fold because its page positions are not equidistant from the gutter. This causes the strip to fold to the right of the gutter.

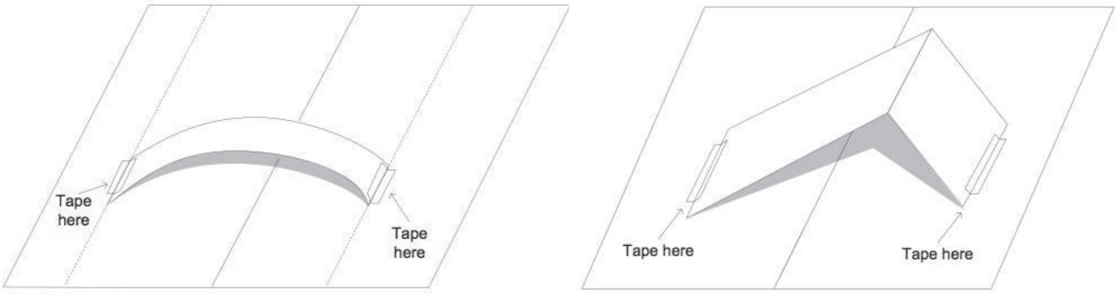



Figure 1. Creating a parallel-fold pop-up (adapted from Benenson & Neujahr, 2009)

## Research Questions

We set out to answer two questions about how children understand and engage in engineering design while constructing pop-up books: (a) How do children report solving problems? and (b) What do children's problem-solving approaches indicate about how they engage in the process of engineering design?

## Method

Participants in our study were 31 children (12 boys and 19 girls) from two third-grade classes in a suburban elementary school in the Midwestern United States. The children were all either eight or nine years old. Data collection consisted of video recording lessons where children worked on paper engineering activities. Seven of the nine lessons were recorded, yielding roughly six-and-a-half hours of classroom video. Additionally, approximately one month after instruction, 29 of the 31 children were interviewed individually. The interviews were semi-structured and designed to elicit information about how children constructed their pop-up books. For example, children were asked questions like, "Tell me about your pop-up," "How does your pop-up work?" or "How did you make that pop-up?" On average, each interview lasted about 7 minutes.

We worked with the classroom teachers to plan the paper engineering lessons. The lessons were based on a 12-part paper-engineering curriculum jointly developed by engineers and educators at City College that included investigation of parallel-folds and their composition (Benenson & Neujahr, 2009). The curriculum emphasized engineering design and had been used previously in several New York City classrooms but had not been used by the teachers in this school. Almost all instruction happened while both classes were co-present in the same classroom. In these instances, one of the two teachers tended to lead instruction. Several times, the classes mixed then split in half. In these cases, each teacher led instruction over the same content independently and in different classrooms. The teachers modified the curriculum greatly when they enacted it. In order to connect it to their required curriculum, they combined it with two other units, researching animals of the world, and writing poems. This resulted in hybrid instruction where children first researched animals of the world (e.g., lions, tigers, anacondas, snowy owls), then learned about, and wrote different types of poems (e.g., acrostic, diamante, haiku), and finally performed paper-engineering activities. The enacted instruction led to children creating their own *animals of the world pop-up poetry books*. On average, each child's book had five pages. Upon completion, the children added their books to the school library (with great pride) so that they, and future generations of students, could check them out and read them.

Our analysis focuses on the individual interviews. These interviews were rich with children talking about the problems they faced during construction. In order to find instances where children reported being confronted by a problem while constructing their book, we followed Jordan and Henderson (1995) and Stevens and Hall's (1998) technique of looking for disruptions or trouble. We began by transcribing each child's interview. We then sought to identify instances of trouble within each interview. We defined trouble as any place where children reported (a) changing their thinking, (b) copying something, (c) being unsure of what to do, (d) asking for help, (e) being constrained by time, or (e) explicitly stating that something was difficult or troublesome. After isolating these instances (in total there were 43), we moved to the second step of our analysis.

Because we were only interested in how children solved problems specific to their pop-ups, our next step was to take a second pass through the instances of trouble to excluded any that did not deal with pop-up construction. Out of 43 total instances, we excluded 27. Many of the excluded instances had to do with aesthetic issues (e.g., how to draw a perfect tiger or how to accurately trace a komodo dragon) that, although they were interesting, fall outside the scope of this analysis. For the remaining 16 instances, we looked for trends in the responses children reported making when they experienced trouble. To uncover trends, we performed an inductive analysis (Thomas, 2006) where emerging themes were developed by both studying transcripts of children's responses in detail and by comparing across transcripts to identify commonalities in children's responses.

## Findings

We classified children's responses to the trouble they reported experiencing while constructing their pop-up books into three categories. We named these categories *troubleshooting, scaling back*, and *emerging ideas*. Children reported troubleshooting to solve problems they experienced with their pop-ups in 5 of 16 instances. When children troubleshot, they tended to focus on retaining their original design goal. Children's troubleshooting consisted of several different problem-solving approaches. For example, some children reported making changes to previous successful pop-ups. That is, when confronted by a problem, children modeled their solution on a pop-up they had built previously, but made slight changes to it. Other children reported taking an iterative approach to problem solving (e.g., some children systematically moved parts of their pop-up to different places in the book after recognizing a problem). Finally, one child reported soliciting help from the teacher to accomplish her design goal.

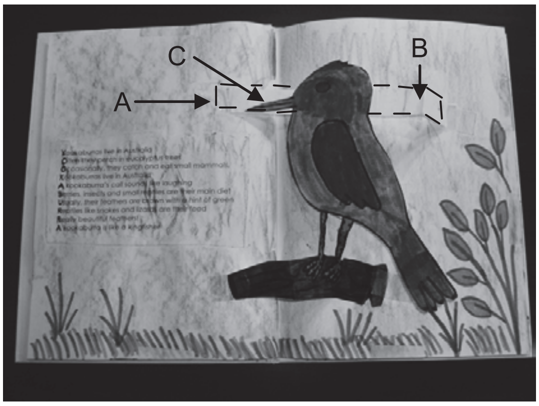
Children also reported solving problems they experienced while constructing their pop-ups by scaling back. Children reported scaling back in 7 of 16 instances. In contrast to troubleshooting (where children worked to accomplish their original design goal), when children scaled back, they tended to alter their original design goal from something more complicated to something less complicated—that is, they satisficed (Simon, 1996). Several children reported that their original plans were difficult or hard and that the new approach (the scaled back approach) was easier. For example, one child who had an idea for multiple pop-up components on the same page (both head and claws popping up) altered her pop-up so that only one component (the head) would pop-up. Another child reported scaling back from an animal's entire body popping up to just the animal's head popping up.

In addition to troubleshooting and scaling back, children reported adopting several other approaches to solving problems they experienced while constructing their pop-ups. Although these approaches may represent responses that could eventually be categories themselves, the small number of instances we isolated in our analysis prevented us from considering them categories at present (thus we combined them to make up the *emerging ideas* category). The four responses in this category included (a) one child explaining a trial-and-error approach, where she attached a pop-up inside her book without knowing what would happen to it—and upon closing and reopening the book—was pleased with the result; (b) one child taking steps to obviate anticipated problems early in the construction of her pop-up; and (c) two children who reported changing their pop-up to address aesthetic issues at the same time as functional issues.

### The Case of Suzie's Kookaburra

This *troubleshooting* example highlights the steps one child, Suzie, took to make her pop-up work in a specific way. In the example, Suzie responded to the interviewer's question about how she made her kookaburra pop-up. Because the 3-dimensionallity of the pop-up is obscured in the picture below, the asymmetric parallel-fold to which Suzie attached her kookaburra's head has been highlighted with a dashed line. This fold resembles the fold in Figure 1.

*S: Well, it took me a while to figure this one out cause at first, I had it like this (A), the page position, was way over here (further left) and um the bend (A) was in the middle (over the gutter) and it (the pop-up) wouldn't work because I wanted it (B) on the side like that (the current position) but it was popping out in the middle (over the gutter) and the tail kept coming like, coming out of the book when the book was closed. So Mrs. D helped me figure out that if you do an asymmetric fold here (B) then it gets like if you do it this way (the current position), it gets it to pop out on this side (right side of the book) and if you do it on the opposite and make it bend here (C), then it pops out on this side (left side of the book).*




Suzie's account provided a detailed report about the decisions she made to ensure her pop-up worked the way she intended it to work. Suzie originally positioned the parallel-fold symmetrically. Positioning the fold (or the bend—as she says) symmetrically caused two problems. First, it caused her kookaburra to pop-up in the middle of the book (possibly occluding part of the poem that Suzie had already pasted to the left side of the book), and second, it caused the kookaburra's tail to protrude from the book when she closed it. With her teacher's help, Suzie switched her fold from a symmetric parallel-fold to an asymmetric parallel-fold. Because Suzie wanted her pop-up to function in a specific way, it required her to make specific changes to her fold. These changes, made to retain her original design goal for how the pop-up would function, seemed to enhance

Suzie's understandings about how her pop-up functioned. By switching from a symmetric parallel-fold to an asymmetric parallel-fold positioned on the right side of the book, Suzie solved both of the problems that she encountered.

### The Case of Jane's Giraffe

In this *scaling back* example, the interviewer asked Jane about how she made her giraffe pop-up. Here, Jane reported that she managed to create a giraffe but scaled back other components of her pop-up. Jane's response is below.

J: *So I—I was trying to get the tree and the bush to pop-up… but it—it wasn't as easy to get those to pop-up as it was for this [the giraffe]. So I have some bushes that I cut out and then taped on. And then I have a tree that I taped on—and then I colored in the sky.*

After reporting that she experienced difficulty trying to get the tree and the bush to pop-up, Jane told how she decided against having the tree and bush pop-up because "it wasn't as easy to get those to pop-up." Instead, Jane taped the tree and bushes to the page rather than making them pop-up. In this instance, Jane solved the problem by altering her original design goal (to have more than one component pop-up) by scaling back some of the functional components of the pop-up and instead adding some aesthetic components to the background.

### The Case of Mary's Koala

This *emerging ideas* example highlights how one child, Mary, reported anticipating and planning to eliminate *measuring* parts of her pop-up. She was the only child who reported obviating the need to measure parts of her pop-up. Mary's response to the interviewer about how she made her koala pop-up is below.

M: *When I first tried to do it, I just tried to stick it [the koala] in right here [in the gutter] and see if it would pop-up. But then um—I had to put it against this [the parallel-fold]—and um… All my pop-ups usually are asymmetric because it's hard to get a symmetric…um fold.*
I: *You found it was easier to do the asymmetric-fold?*
M: *Cause it doesn't matter—like it [the right page position] could be way over here [further right] but when it's symmetric, you have to get it all—like you have to measure it and things like that.*

In her answer, Mary reported that symmetric pop-ups are hard compared to asymmetric pop-ups because they involve measuring; therefore, she usually makes asymmetric pop-ups. When she explains, "when it's symmetric… you have to measure it," we take it to mean she understands that in order to make a symmetric pop-up, the distance between the page position and the gutter must be the same on either side of the fold. In contrast to symmetric pop-ups, when children constructed an asymmetric pop-up, they did not necessarily need to measure because they could "let the book do the fold" (as shown in Figure 1). By consciously favoring asymmetric folds and thereby obviating measure, Mary eliminated functional considerations that come along with planning for symmetry or asymmetry in her pop-ups. Essentially, by taking advantage of "the book doing the fold" for her, Mary saved herself considering issues that stem from measuring.

## Discussion

In this pilot study, we observed children using diverse problem-solving approaches when constructing pop-ups. Furthermore, we noticed children's design goals were related to their problem-solving approaches. That is, children sometimes solved problems to reach their goal, and sometimes changed their goal to solve the problem.

Although we do not consider one child's problem-solving approach to be more or less valid than another, we do recognize that some problem-solving approaches are more emblematic of engineering disciplinary practices and engineering *habits of mind* (i.e., concepts or skills that engineering curricula strive to emphasize) than others. For example, in the troubleshooting example, Suzie demonstrated an approach to problem solving that aligned closely with established engineering disciplinary practices. Her approach was purposeful (she had a design goal), systematic (she did not leave her pop-up's motion to chance), and social (she drew on the teacher's knowledge of pop-ups by asking for help). Additionally, she sought to optimize her pop-up by generating a solution through repeated cycles of analysis and evaluation. These problem-solving approaches are most akin to the skills and concepts that accompany engineering design in typical P-12 engineering curricula.

Although Jane and Mary came up with resourceful approaches for solving the problems they faced while constructing their pop-ups, their approaches were less like the approaches engineering curricula espouse. For example, Jane switched her design goal. By switching her design goal, she eliminated the constraints she had originally placed on herself (i.e., that the tree and bushes needed to pop-up). Once she eliminated these constraints, the problem did not exist to solve anymore. Similarly, Mary formulated a goal that was based on eliminating the need to think carefully about a specific aspect of her pop-up (measure). Mary removed measure from the components she had to plan for. As a result, Jane and Mary minimally participated in sustained troubleshooting□ and in a way, avoided it. Essentially, both children identified a problem and specified a solution but eliminated the need to analyze or evaluate alternative solutions.

This study has several limitations. First, the interviews were post-design, and were therefore re-representations of what children actually did and thought. Also, because we relied on children's self-reports, we identified a small number of instances of trouble related to pop-up function that represented a cross-section of the entire class (about one third of the children reported functional trouble). Therefore, our sample was not completely representative of the class. In future iterations, we intend to perform analyses on discourse and actions situated within the paper engineering instruction to see the range of children's problem solving approaches in context.

□espite these limitations, our findings nonetheless provide insight into the problem-solving approaches children used while constructing their pop-up books and therefore have implications for elementary grade engineering design instruction. Originally we did not foresee the need to establish a framework for guiding children toward a practice of troubleshooting while they participated in paper engineering activities. In future iterations of working with children paper engineers, we hope to engender an ensemble of recurrent activities that promote children adopting a practice of troubleshooting. Our goal is to design instruction so that there is a normative expectation that children will value and engage in specific activities (e.g., investigation and experimentation, solicitation of others' perspectives, modeling, and mathematizing) in the service of troubleshooting. We con□ecture that installing a practice of troubleshooting could aid children in finding solutions to emerging or anticipated challenges in their designs. The instructional challenge will be to develop forms of support for the practice of troubleshooting of sufficient generality yet firmly grounded in design difficulties that children identify. We expect that repeated opportunities to participate in troubleshooting practices in contexts of paper engineering could benefit children in other engineering design contexts.

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