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Engineering-Based Problem Solving in the Middle School: Design and Construction with Simple Machines

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Abstract

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Engineering-Based Problem Solving in the Middle School: Design and Construction with Simple Machines

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Abstract

Incorporating engineering concepts into middle school curriculum is seen as an effective way to improve students' problem-solving skills. A selection of findings is reported from a science, technology, engineering and mathematics (STEM)-based unit in which students in the second year (grade 8) of a three-year longitudinal study explored engineering concepts and principles pertaining to the functioning of simple machines. The culminating activity, the focus of this paper, required the students to design, construct, test, and evaluate a trebuchet catapult. We consider findings from one of the schools, a co-educational school, where we traced the design process developments of four student groups from two classes. The students' descriptions and explanations of the simple machines used in their catapult design are examined, together with how they rated various aspects of their engineering designs. Included in the findings are students' understanding of how their simple machines were simulated by the resources supplied and how the machines interacted in forming a complex machine. An ability to link physical materials with abstract concepts and an awareness of design constraints on their constructions were apparent, although a desire to create a "perfect" catapult despite limitations in the physical materials rather than a prototype for testing concepts was evident. Feedback from teacher interviews added further insights into the students' developments as well as the teachers' professional learning. An evolving framework for introducing engineering education in the pre-secondary years is proposed.

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Introduction

Incorporating engineering-based problem solving within students' learning of mathematics, science, and technology is gaining greater attention across many nations, with science, technology, engineering and mathematics (STEM) in K-12 increasingly regarded as an essential component of progressive 21st century education (e.g., Berland, 2013; English & Mousoulides, 2011; National Research Council, 2009a; Zawojewski, Hjalmarson, Bowman, & Lesh, 2008). Indeed,

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educating "a more scientifically literate citizenry" is one of the core goals of STEM education (Shaughnessy, 2013), yet it remains limited in the elementary and middle schools, especially with respect to the inclusion of engineering experiences (Holmes, Rulfs, & Orr, 2007; Stohlmann, Moore, & Roehrig, 2012). As the National Research Council (2009b) emphasizes, it takes years or decades to build the capabilities required by societies: "You need to generate the scientists and engineers, starting in elementary school and middle school" (p. 9).

Echoing these sentiments, numerous educational bodies have lobbied in support of an increased focus on STEM in schools, especially for underrepresented populations. As Shaughnessy (2013) noted, the National Council of Teachers of Mathematics (NCTM), for example, is advocating that STEM education becomes a national priority where students are inspired to pursue these fields in school and beyond, and where increasing the qualifications and retention of STEM teachers is paramount. Recent US policy initiatives are now targeting STEM issues as can be seen in the Common Core State Standards in English, mathematics and science (Common Core State Standards Initiative, 2012). Other initiatives such as the US National Engineering Academy's Grand Challenges for Engineering are adding to endeavours to advance STEM participation (National Academy of Engineering, 2012).

Likewise in Australia, recent reports have stressed the importance of enhancing students' engagement in STEM fields, which are seen as powerful vehicles for stimulating innovation, invention, and economic development (e.g., Department of Innovation, Industry, Science, and Research (DIISRTE), 2011; Engineers Australia, 2009; Tytler, Osborne, Williams, & Cripps Clark, 2008). The recently implemented Australian Curriculum in mathematics and science, and the draft technologies curriculum (ACARA, 2013) incorporate problem solving, reasoning, and design processes, although specific reference to engineering-based experiences is limited. Although efforts are being made to increase participation in STEM within Australia, the need for a strong national policy in this regard has been emphasized in a recent report on international comparisons of STEM education (Australian Council of Learned Academies, 2013).

In our own efforts to improve STEM education in the middle school, we implemented a three-year longitudinal study across grade levels 7–9 in three schools. In this paper, we report on a selection of findings from a STEM-based unit in which students in the second year (grade 8) explored engineering concepts and principles pertaining to the functioning of simple machines. The culminating activity, the focus of this paper, required the students to design, construct, test, and evaluate a trebuchet catapult. We consider findings from one of the schools, a co-educational college where we traced the design process developments of four student groups from two classes. The students' descriptions and explanations of the simple machines used in their catapult design are examined, together with how they rated various aspects of their engineering designs including ways in which they would improve their designs.

Engineering Education in the Middle School

The introduction of engineering education within the elementary and middle school reflects the growing concerns of several nations that face an increased demand for, and declining supply of skilled workers in engineering and allied fields. The number of graduating engineers from U.S. institutions, for example, has declined in the past decade (OECD, 2006), whereas in Australia, the number of engineering graduates per million lags behind many other OECD countries (Taylor, 2008). To complicate matters, engineering does not have a high public profile in many nations. For example, a recent report, *Engineering our Future* (National Grid, n.d.), revealed that, although there is a cursory acceptance of engineers and engineering among young people, parents, and teachers in the UK, there are negative perceptions underlying this acceptance, such as a lack of knowledge and appreciation of the role of engineering in society. Other studies (e.g., the ROSE project: Sjoberg & Schreiner, 2010) have shown a negative correlation between students' attitudes to STEM and a nation's development index. For a nation to be competitive internationally and strengthen economic growth, it needs a growing body of well-educated professionals in the STEM fields (National Research Council, 2009a; National Research Council, 2009b; OECD, 2006).

In addition to fostering young students' appreciation and understanding of engineering in society, engineering education can contribute to their learning across many areas of the curriculum. It not only contextualizes mathematics and science principles and promotes design processes, but can also enrich students' learning in their studies of technology, literacy, history, and geography. For example, projects that incorporate investigations of engineering feats across time and locations can extend students' appreciation and awareness of the many ways in which engineering has shaped and improved societies over the centuries (Hudson, English, & Dawes, 2013). This interdisciplinary perspective is now extending to the arts, such as STEAM programs that acknowledge the role of the arts in today's world with a focus on creativity, innovation, and design. Some nations, such as South Korea, are utilising STEAM programs in schools to increase participation and success in STEM involving interdisciplinary problem solving (Korean Foundation for the Advancement of Science and Creativity, n.d.).

Of particular importance in engineering education, and a strong focus of our work in schools, is engaging students in engineering design processes as they solve challenging yet meaningful real-world problems. Investigating such design processes in the middle school, however, remains in its infancy despite the recognized contributions it can make to problem solving across disciplines (Brophy, Klein, Portsmore,

& Rogers, 2008; Diefes-Dux, Hjalmarson, Miller & Lesh, 2008; Wicklein, 2006).

Engineering Design Processes in K-12 Education

It has been noted frequently that an understanding of engineering design processes is at the core of engineering (e.g., Cunningham & Hester, 2007; Hsu, Cardella, & Purzer, n.d.), together with the creation, application, and adaptation of mathematical/scientific models that that can be used to interpret, explain, and predict the behaviour of complex systems (English & Mousoulides, 2011; Zawojewski et al., 2008). The cyclic processes of modelling and design are very similar: a problem situation is interpreted; initial ideas (initial models, designs) for resolving the situation are initiated; a promising direction is selected and expressed in an experimental form; the idea is tested and the resultant information is analysed and applied in revising (or rejecting) the idea; the revised (or a new) idea is expressed in an experimental form; and the cyclic process is repeated until the idea (model or design) meets the constraints specified by the problem (Magiera, 2013; Zawojewski et al., 2008).

Addressing engineering design processes as part of the middle school curriculum can significantly improve students' problem-solving abilities together with an understanding of core concepts and principles of a discipline (Borgford-Parnell, Deibel, & Atman, 2010; Brophy et al., 2008; Diefes-Dux, Zawojewski, & Hjalmarson, 2010; English & Mousoulides, 2011; Stoner, Stuby, & Szczepanski, 2013). As Borgford-Parnell et al. (2010) emphasized, design often involves working on complex and ill-structured problems that feature ambiguity, multiple solutions, and few, if any, defined rules. The importance of middle school students working on challenging and motivating learning experiences with high cognitive demand has been stressed repeatedly in the literature (e.g., Brophy et al., 2008; Lambert & Stylianou, 2013; Silver, Mesa, Morris, Star & Benken, 2009; Stoner, et al., 2013), with such experiences contributing to the development of creative, flexible, and innovative thinking skills. Students are thus better placed to deal with the complex issues that arise in their present and future lives, including those that involve mathematical and scientific situations (e.g., Borgford et al., 2010; English, Dawes, Hudson, & Byers, 2009; National Research Council, 2009a).

Although there are various frameworks and approaches for developing engineering design processes (e.g., Cunningham & Hester, 2007; Holmes et al., 2007; Stoner et al., 2013; Wicklein, 2006), little attention has been given to ways in which elementary and middle school students evaluate their designs and identify ways of improving their initial designs. Despite the complexity of design processes, some research has shown that even young children have an emerging capacity to undertake simple design work such as imagining, planning, constructing, and evaluating (e.g., Fleer, 2000; Cunningham & Hester, 2007). In Fleer's study, for example, preschool children developed designs for creating a friend or home for a lonely mythical creature living in their garden, and determined a list of materials they would need for their construction. Subsequent interviews revealed a capacity to clearly explain their initial intentions and plans and why their design did not meet the criteria they had generated.

Students' evaluation of their designs can reveal the extent to which they identify and understand core concepts and principles pertaining to both engineering and the curriculum content. Selecting appropriate content can be a challenge in itself, however, with the need for rich and appealing links to the discipline knowledge to be learned (Brophy et al., 2008). In the present case, the core content formed a unit within the students' science/mathematics curriculum incorporating the nature and functioning of simple machines, and how they can interact in producing a desired product, namely, a catapult.

Engineering-Based Contexts: Simple Machines

A knowledge and understanding of simple machines—their properties, how they function, their ubiquity in everyday life, and their key roles in engineering achievements—is fundamental learning in students' development of scientific and mathematical literacy (e.g., Dotger, 2008; McKenna & Agogino, 2004; Taylor, 2001). The importance of students' construction of simple machines, including drawing plans and describing and communicating their understandings, has been emphasized in literature for classroom teachers (e.g., Dotger, 2008; Lancor & Schiebel, 2008; Taylor, 2001).

There appears very limited research on middle school students' experiences with simple machines, especially with respect to engineering-based units of study. One such research program (McKenna & Agogino, 2004) developed a learning environment to support middle and high school students' mechanical reasoning and understanding of simple machines. Their SIMALE project (the Simple Machines Learning Environment) was created to support "reflection, collaboration, and presentation of concepts from multiple perspectives and contexts" (p. 97). The findings showed significant improvements in learning across the three categories of assessment, namely, analytical problem solving, conceptual understanding, and the ability to draw and model. This improvement occurred regardless of the three intervention types and focus used, namely, computer simulations, use of hands-on Lego experiences, and both.

A core feature of the SIMALE project was presenting students with opportunities to apply their understanding of simple machines across multiple contexts. The intervention types provided different levels of sophistication in the use of lever and pulley devices in various situations. Finding relevant and meaningful contexts in which to introduce the concepts of simple machines can be challenging (Taylor, 2001). However, the interdisciplinary nature of engineering

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education enables appealing contexts to be utilized, such as the historical role of catapults in the present study.

A significant implication from McKenna and Agogino's project is the important role of collaboration—their students worked in small groups to share and test ideas, clarify interpretations of the problems, and explicitly express their thinking and understanding. Students' verbal discussions, illustrations, graphical representations, and written explanations opened windows into their understanding of simple machines. The power of collaboration was also evident in Lancor and Schiebel's (2008) study involving college physics students and elementary grade students, where the former engaged their younger peers in a simple machines activity. The learning of both was enhanced, with the college students gaining a better understanding of physics principles and awareness of their own learning, while the young students retained their learning of simple machines, how they function, and how they simplify life.

Despite these few studies, there remains an apparent dearth of research investigating simple machines as a rich basis for incorporating engineering within the elementary and middle school curriculum. The present study offers one example of how this might be accomplished. Specifically, for the findings reported here, our research questions address the following:

- *Students' description and explanation of the simple machines used in their design*. In particular, how many simple machines did the students identify and did they include reference to the classes of levers used? Did the students indicate how the machines were simulated by the materials used? Were they able to explain how the machines operated in the catapult's design and refer to engineering principles? Did the students indicate how the machines interacted in operating the catapult? Could they explain why their design was applied?
- *Students' evaluation of their designs*. Specifically, to what extent did the students consider their design to comply with the given constraints? How practical, sturdy, and creative did they view their design? How efficient did they consider their resource use?
- *Students' perceived improvements to their design*. In what ways did the students indicate they could enhance their design?

Methodology

Student and Teacher Participation

Three private Queensland (Australia) schools (two single sex and one co-educational) were involved in the three-year, longitudinal study within the middle years of schooling (grade levels 7–9). This paper addresses the second year of the study with attention given to the co-educational school, and in particular, four focus groups of students (four students per group) across two classes (16 such students from a total of 58; age range 12–14.5 years). We restrict our reporting to this particular school as the teachers chose to enrich the learning experiences beyond what we had planned across the three schools, resulting in greater insights into the students' understandings of simple machines.

The female teacher of one of the two classes was an experienced secondary science teacher, whereas the other teacher was in his second year as a science and mathematics teacher. Our observations of their teaching indicated they were confident and competent teachers who could direct students effectively to their tasks and ask guiding questions to facilitate a positive learning environment. Their involvement in the study was essential, with their in-depth knowledge of their students and the curriculum a key element. We thus considered it more appropriate that the teachers, themselves, arrange their students into groups with consideration of abilities, personalities, and gender.

The teachers' involvement included regular teacher briefing and debriefing meetings throughout each year. The meetings entailed reviewing their mathematics and science programs, planning learning experiences that targeted core curricula goals and themes, reviewing the students' progress, and preparing future activities based on students' developments in the previous experiences. In essence, the teachers were co-designers in the learning experiences, with the researchers providing advice on implementation. The teachers and researchers did not intervene directly in the students' group work addressed here. Learning was only facilitated where necessary, such as responding to a student's query by posing a thought-provoking question in return.

Learning Experiences

As background to the second year of the study, we indicate briefly the students' introduction to engineering education in their first year (grade 7). The students began by exploring the world of engineering and its different fields, investigating eminent engineers, and researching major global engineering feats. Given the extensive city constructions taking place at the time, this first year focused mainly on civil engineering where students investigated civil engineers and their work, and explored the types and structures of bridges in their local area. Students subsequently engaged in the design, construction, and evaluation of a small-scale truss bridge within monetary and resource constraints.

Exploring Simple Machines: The Catapult Challenge

In the following year (grade 8), the students completed two comprehensive units of activities, the first of which is the focus of this paper, namely, the simple machines unit.

The unit extended over 18 × 45-minute lessons and provided background information on simple machines, together with an experimental preliminary activity for understanding associated key concepts; these understandings were then applied to the design and construction of a catapult. The preliminary experiences engaged the students in investigating properties of inclined planes, pulleys, levers (1st, 2nd, 3rd classes), and wheels and axles. They also explored simple machines as force and speed multipliers, investigated work related to energy, and calculated mechanical advantage.

The main activity addressed here required students (in groups of four) to design, construct, test, and evaluate a trebuchet catapult. Two lessons were devoted to constructing the catapult, one lesson to testing and evaluating the catapult, and one lesson to providing a written explanation of conceptual understandings. The catapult's effectiveness was tested by flinging a marshmallow to hit a bull's eye target at a two-metre distance. The appendix presents the main components of the activity. Students were to draw their own designs first, then decide on and create a group design, with instructions to include labels, specifications, and brief descriptions of how each part would function. They were to then record a description and explanation of the simple machines used in their design.

On testing their catapult, the students were to reflect on its effectiveness by responding to the questions: How does your design comply with the design brief? What is practical about your design? What makes you think it is sturdy and will work? What is creative about your design? What simple machines does your catapult use in the design? How efficient is your catapult in using resources? Why do you think so? What else could you improve with your design? Why?

Teacher Interviews

At the end of each year we interviewed each of the participating teachers individually, inviting them to comment freely on various aspects of the program. Included in our questions were their satisfaction with the activities, aspects they considered worked well and those that could be improved, what they considered their students had learned, and the teachers' professional development in implementing the activities including the effectiveness of the collaborative development.

Data Collection Methods and Analysis

Multiple sources of data collection were undertaken, including audio and video recording of all the focus group work and whole class discussions, scanning of students' workbooks, and photographing of the students' creations. The end-of-year teacher interviews were also transcribed.

The focus groups were audio and video recorded during the last four 45-minute lessons of the simple machine unit. Students used workbooks (one workbook per student) to record their thinking about the key engineering concepts applied to designing, constructing, testing, and evaluating a catapult. Once scanned, these documents were returned to the students. As one focus group student was absent for some of the lessons, the responses of only 15 of the 16 focus students across the two classes are reported here.

Data analyses involved ethnomethodological interpretative practices, which incorporated iterative refinement cycles for analyses of students' learning (Lesh & Lehrer, 2000). Data were progressively reviewed, transcribed, coded, and examined for patterns and trends in the students' developments using constant comparative strategies (Corbin & Strauss, 2008). Specifically for the data reported here, students' written workbook responses were repeatedly reviewed and coded to address the research questions, with the coding refined over several months to identify the major understandings. Inter-rater reliability was established through multiple sharing and refining of the coding by the authors, with the process commenced by the first author. For example, in analysing students' description and explanation of the simple machines in their design, an initial code of "explains how the simple machine contributes towards the catapult's design" was expanded to three codes, namely, factors 2, 3, and 4 described in the next section. Where necessary, member checks were made with the research assistants.

Results

In reporting our results, we first consider how the focus group students described and explained the simple machines used in their design as gleaned from their student workbook responses. We next look at the various factors they offered in evaluating the design of their catapult, as noted in their workbooks. Following this we consider the students' suggestions for improving their design. Finally, we present excerpts from the teacher interviews that provide some insights into the teachers' perceptions of their students' learning and their own professional development.

Students' Description and Explanation of the Simple Machines Used in Their Design

In analysing the focus group students' responses to this component, five main factors were identified as indicative of their understanding and appreciation of simple machine use in their design, specifically: 1. The number of simple machines identified and, for the identification of levers, the class of lever indicated; 2. An indication of how the machines were simulated by the materials used; 3. An explanation of how the simple machines operated in the catapult's design, and whether reference was made to appropriate engineering principles; 4. As an extension of

the last factor, an indication of how the simple machines interacted in operating the catapult; and 5. An explicit indication of why the design involving the simple machines was applied.

Table 1 shows the numbers of student responses for each of the five factors. Of the 15 student responses, all but one student identified multiple simple machines, with nine citing three or more. Nine students also recorded the class of lever they identified, with five students explaining why this was the case, such as Martin's description: "A third class lever consists of a fulcrum at one end and the load at the other end and the effort is in the middle." Further examples are given in the student responses that follow.

All but two students clearly indicated how the machines were simulated by the materials they used (e.g., "The wedge used was a pushpin. The lever used was a spoon"), with their explanations including how the machines operated in the catapult's design. Their responses varied in the depth, however, with some including explicit reference to underlying principles ($n = 8$) and others suggesting implicit or no reference ($n = 6$; one of these students did not indicate material simulation, however). Nine students also explained how their simple machines interacted in operating the catapult, with seven of these students justifying their use of simple machines in their design.

To illustrate some of the above understandings, we reproduce aspects of three students' responses. Peta, for example, identified the creation of a complex machine and not only indicated how the simple machines were simulated by the materials but also the properties they featured. Her description suggests she understood how the practicalities of the resources enabled the engineering and scientific concepts to be applied in designing a workable catapult. Peta also drew on her mathematics learning in mentioning how she utilized her base and why she included triangular frames. She explained:

"The simple machines were all put together to work as a complex machine. The spoon was used as a lever. It had a load, pivot and counter-weight/effort. The load was the marshmallow in the spoon. It was the projectile. On the other end of the spoon was the counter-weight. That end was attached to the base of the whole catapult. In the centre was the pivot. The pivot was a short paddle pop stick. To keep it high, on either end there were two triangular frames attached to the base and short paddle pop. The load, pivot, and counter-weight being where they are, makes it a 1st class lever."

Table 1
Number of student responses for each factor in the description and explanation of simple machines.

Factors Addressed	Student Responses/15
No. of machines; class of lever	14
How machines were simulated by materials	13
How machines operated in design; reference to engineering principles	8
How simple machines interacted	9
Indication of why design applied	7

In the next example, Noela displays a recognition and appreciation of the simple machines her group used, how they were simulated by the resources, why the simple machines were chosen, the engineering principles underlying their functioning, and the need to keep in mind the problem constraints. Noela's explanation also indicates how she could readily connect abstract concepts, such as potential and kinetic energy, to the physical materials and their interactions in achieving the desired outcome, such as generating this energy. She was also cognizant of the mathematical constraints imposed on the design, lamenting that the cost factor was a disadvantage.

"Our catapult, 'The Epic Failure,' used only a few simple machines yet still worked efficiently. The most important simple machine used was a lever. Our group's lever was made of a spoon attached to a cotton reel, which was then attached to the base. The design was applied mainly because it would stick to the budget and it was easy and efficient. We decided that a lever was the best way to fling the load at the target because applying a lot of effort on the spoon creates potential energy. This potential energy will then become kinetic when the effort stops being applied and the load will fling and (hopefully) hit the target. A wheel and axle was also used to get the catapult up the ramp. The wheels were made of cotton reels and dowel was used as the axle. A wheel and axle was used because not only does it make it easy to get up the ramp, but it also gives the catapult's fling more force by rolling forward. The only disadvantage was the cost."

Like Peta, Jacinta indicated an understanding of how simple machines operate to form a more complex device for accomplishing the problem goal. She clearly identified how the machines were simulated by the materials and how they interacted in operating the device. She appeared to have a solid understanding of the scientific and engineering principles underlying the machines' operations. Furthermore, Jacinta displayed an appreciation of the important contributions of collaborative group work in producing a more effective design.

"Simple machines are devices that exist to make work easier. When two or more simple machines work together they form a complex machine. The catapult is a complex machine. The final catapult design the group decided on incorporated the strongest features of each of the group's member's individual design, which resulted in a highly improved catapult in comparison to the individual designs. On the catapult there were several simple machines, and an additional simple machine to move the catapult up the ramp."

"The first and most obvious simple machine was a wheel and axle. The wheels on the bottom of the catapult existed

simply to move the device. The cotton reel acted as the wheel and the dowel and rubber bands formed the axle. Another simple machine used was the spoon, thumbtack and paddle pops, which acted as a second class lever, with the effort on the same side as the load, and the fulcrum on the other side. The spoon, thumbtack and paddle pops formed the actual device that the object was placed onto, to be flung. To pull the catapult up the ramp, the simple machine that was used was a pulley. To make the pulley, a cotton reel and a piece of string were used. The string was then wound around the cotton reel. When the effort is applied to one side of the string it causes the opposite side of the string to lift up. The string was attached to the front of the catapult."

Students' Evaluation of Their Design

On completion of their catapult and its testing, the students reflected on various aspects of their design. Specifically, they were to rate seven components on a scale of 1–5, with 1 indicating "not so good" and 5 denoting "excellent." Descriptions for in-between ratings were left open to enable students to make their own judgements regarding their design's effectiveness.

The components included: 1. How does your design comply with the design brief? 2. What is practical about your design? 3. What makes you think it is sturdy and will work? 4. What is creative about your design? 5. What simple machines does your catapult use in the design? and 6. How efficient is your catapult in using resources? For the seventh component, the students were asked, "What else could you still improve with your design?" The students were to also explain why they chose each rating. Following this, the students were to select another group and rate its design in the same way.

We restrict our findings here to the students' evaluation of their own designs, and consider in greater detail their responses to the creativity and improvement aspects, which provided extended rich data. Including the creative component was considered important, given that creativity in engineering innovations is gaining increased recognition "as a necessity, rather than an accessory in engineering design" (Charyton & Merrill, 2009 p. 145).

Design compliance

Of the 15 focus group responses, 13 rated their design as either 3 or 4, with one student recording 3 1/2 and another 4 1/2. It would seem that, on the whole, the students considered their design to comply with the constraints given. For example, one student who gave a rating of 4 explained: "The structure of the catapult remained mostly the same as the initial design brief. A couple of improvements were made, for example, to connect the wheel part of the machine to the catapult, it was found to be more beneficial, strength wise to use string as opposed to using sticky tape."

Practicality

Again, the students' ratings clustered around 3 and 4 (6 and 7 such responses respectively), with two students considering their design to have limited practicality (rating of 1 or 2). The student who rated their design as 2, noted that "the only practical thing about it is that the spoon was held back with great force," suggesting some understanding of the scientific and engineering concepts underlying their design. Likewise, an awareness of how the properties of simple machines impact on design was evident in a student who rated practicality as 4: "The third class lever is very practical for throwing projectiles."

Sturdiness

Ratings at the lower end of the scale were recorded for students' assessment of how sturdy a catapult they considered their design to generate. The students' ratings ranged from 1 to 4 with just over half being 1 or 2, with some reference to the weaknesses of the materials (e.g., "It wasn't necessarily thought to be 'sturdy' because the sticky tape wasn't strong enough to hold everything in place for it to be a success").

Creativity

In contrast to the previous components, students' assessment of their design's creativity spanned the entire range with the most prevalent ratings from 2 through 4. One student rated their design as excellent (5), whereas 9 students recorded 3 or 4. Their explanations for their decisions included reference to design features such as the use of a pulley system, mathematical features such as triangular supports and a substantial base, and to how resources were used or combined in the design. Comparisons with other groups' design were also mentioned. Below is a selection of responses with a rating of 3 or 4.

A. The reason our design was creative was because not many other catapults had designs which had a full base of paddle pop sticks, some just only had a frame. Also, almost no groups had a pulley system.
B. Unlike real catapults, this one had a full base with no gaps. It didn't use string to attach all parts. Instead it use (sic) stick tape.
C. Instead of a frame to hold up the spoon so it's stable when it launches, it uses a cotton reel and the base itself to hold it up. The cotton reel is attached to the base and the spoon rests against it making it the fulcrum of the lever. The base is used also to stabilize the spoon because some of the spoon is inside the base. It is a simple design.

It is interesting to note how the student who gave the third response above drew on her understanding of simple machines and engineering design principles to justify the creativity of her catapult construction. In her workbook she

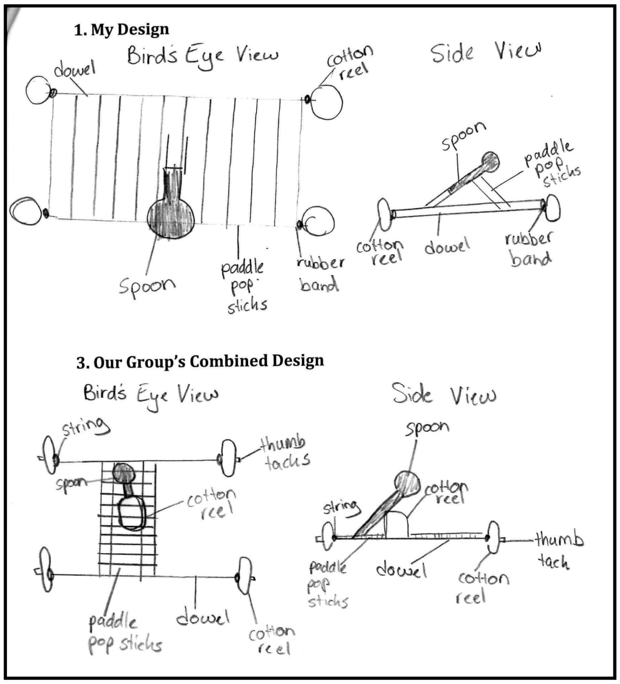

Figure 1. Student's and group's designs displaying two perspectives.

presented two designs, her own and that of the combined group, which appear in Figure 1. Her display of two perspectives nicely illustrates how her own design features were incorporated within the group's design, with the spoon and cotton reel apparently replacing her original paddle pop stick to form the lever's fulcrum.

Use of simple machines

The students' evaluation of their use of simple machines was favourable, again with 13 ratings of 3 or 4. One student (rating of 3), for example, explicitly mentioned the five simple machines they had explored before the Catapult Challenge, explaining that "There are a few different simple machines used, such as the inclined plane, gears, wheel and axle, lever and the pulley system. Everything was shown in the design, and they all worked as planned."

Efficiency

The students were not as satisfied with their efficiency in using the resources, with 10 of the 15 responses ranging from 1 to 3. Reasons for this inefficiency were mixed, including those who stated they had spent the entire monetary allocation without generating what they considered a successful catapult. Others explained that although they had not depleted their entire budget, they could have made their catapult more efficient by using different materials. Others noted that they had some funds remaining. The students' recognition of the resource limitations placed on their design was evident in their responses, suggesting an awareness of the importance of constraints in engineering design. In particular, the budgetary constraints drew on the students' mathematical skills in estimating, calculating, and monitoring the use of monetary funds.

Students' Perceived Improvements to Their Design

Inviting students to suggest ways of improving their designs provided opportunities for further reflection on the foregoing design components. Their responses mostly clustered around the 3 and 4 ratings (12 such responses), with a variety of reasons offered for how their design might be improved. These included improving specific design aspects such as the construction of the base (with or without mention of simple machine use), addressing material weaknesses including their impact on the overall design, identifying better material combinations, and altering mathematical constraints such as increasing time, resources, and budget. Of particular interest to this study are the students' references to design features and underlying engineering principles. Ten students gave explanations of this nature, examples of which appear below. It is interesting to note in the first example, a possible increase in confidence in being able to achieve the task, with the group suggesting a name change from "The Epic Failure" to "The Epic Achievement."

A. If I could improve anything I would make a pulley to get up the ramp so that it would be easier and that more simple machines would be used. I would also stick the base together a little more so that it didn't fall apart so often. Another major change could also be the name. Instead it could be called "The Epic Achievement."
B. The base could have been made more stable. By having sticks going across like a fence. The frames on either side could have been tied with string instead of sticky tape.
C. The power and distance when projecting the marshmallow.
D. We could improve the stability of the wheel, and the angle that the spoon was on. So it would be a better aim.
E. The catapult that the group constructed could be improved in many ways, given more time, more resources, and a larger budget. The catapult was not stuck together very well with the tape and the lever was not put in the right place. Overall the catapult was alright, but if given the chance the catapult could be greatly improved.

Perceptions of Student and Teacher Learning

Further insights into the outcomes of the study were gleaned from the teacher interviews. Specifically, we give consideration to the two teachers' perceptions of their

students' learning, together with their own professional development including working collaboratively with the other teachers in developing the activities. Their feedback provided valuable suggestions for improvement.

The female teacher commented on the enjoyment of the hands-on experiences but indicated that time was a limiting factor in the learning for some students: "They really, really love the hands-on and being able to manipulate. One of the things I think they had some difficulty with was the time aspect because they weren't able to explore things as much as [they'd like]. Some kids can just put things together and they know it works, they're that way inclined. Other kids needed more time to be able to say, 'we put this together like this, that doesn't work, I need to try something else.'" The teacher also highlighted the challenging aspect of the problem constraints: "One of the things they found was challenging was the limit of resources, you know, can we have a hot glue gun, can we have this, can we have, well no, you've got to work with what you've got and that they found challenging; so I think they learnt from that experience that sometimes you've got to work with what you've got in a, not just in this sense, but in a much broader sense as well."

The male teacher indicated improved student understanding of and engagement with simple machines, but at the same time pointed out that some students experienced difficulties in linking the core mathematics and science concepts. The latter aspect, however, was not confined to the present activities, as can be seen in snippets from his interview:

"I think they certainly gained that deeper understanding of the world around them just generally from looking at how their faces lit up when you were talking about different simple machines and 'oh yeah!' and then suggesting different ones and that sort of thing so they were definitely engaging with that aspect of it. From a mathematics perspective, cause I have the same class for mathematics as well, um, even though I had a core class and it's the same kids for maths and science, there's still a great distinction between what is done in maths and what is done in science…if it was timetabled that you had, you know you have so many classes and you could do with them what you would [like], which wouldn't work for a number of reasons… but the students still saw science as science and maths as maths and I don't actually think that the things we did with ratios, the work we did with graphs, necessarily translated for every student…"

Both of the teachers' feedback on their own development including working collaboratively with the other teachers was positive. Opportunities for rethinking the extent of teacher direction, an increased focus on student investigations, and enhancement of the Australian Curriculum were identified. As the female teacher explained, "I learnt to let go. I guess I'm, with having so many practical activities, I'm used to a certain control in a classroom, when you say to them here's your activity, sometimes they forget to read the instructions so what I have found this year, implementing it again, I'm actually being more prescriptive about going through the steps, and I found yesterday, I wasn't prescriptive enough, so I still maintained a little bit more control of the classroom and then let them go and explore that, and if they make mistakes, that's okay."

With respect to the Australian Curriculum, the teacher commented, "I guess it fits very nicely with the Australian Curriculum where it is more an investigative pedagogy, where you do the hands-on activity and investigate how the different things work with it, so it does lend itself very nicely to that and um particularly as I teach senior and it is probably more prescriptive, you need to um, with the junior school you can be less prescriptive and more hands-on and more interactive and more investigative."

Working collaboratively with the other participating teachers was viewed in a positive light, with motivation, engagement, and teacher learning rated highly. For example, the female teacher expressed a similarity between teacher and student learning: "I think as teachers we're more engaged with the activity. Same as the kids, if they're involved in the activity design they're more engaged with it; I think the same thing happens for teachers as well. I don't think that makes a unique scenario there. Um, I think we also, I think you've got a different pool of ideas that can come together and you can come up with some more, some different strategies, um, that whole brainstorming idea is a really good one."

In a similar vein, the male teacher praised the learning benefits of working with his peers: "I think the tasks themselves were really good, the tasks were sort of collaboratively done over a bunch of different schools; you got a whole bunch of different perspectives; it meant that a whole range of interests were catered for, a whole range of abilities were catered for. Some things like, because they were done by different schools, things like the cohesion might have been lacking in some areas, um just from lesson to lesson and I think to a certain extent because we've revised the unit for this year, we're currently running it, I think the cohesion is a little better cause someone's reviewed it…"

This teacher also noted the networking benefit of the collaborative work: "I think it was an enlightening experience, especially working with teachers from other schools. It's good to make contacts as well and I've since attended a conference and caught up with um another of the teachers from the project who's doing a, um participating in another project um, on differentiation of mathematics so it's really, it's a network that way."

Discussion

We have described one approach to incorporating engineering-based problem solving within a school's

science/mathematics program. The simple machines unit formed core content of the students' curriculum during the eighth grade. The design, construction, testing, and evaluation of their catapult as the culminating activity enabled the students to apply their initial learning about simple machines to solving a stimulating and challenging engineering problem.

The findings from the focus group students indicated that they could identify multiple simple machines, with an understanding of their properties and how the machines were simulated by the resources provided. Sixty percent of designs included three or more simple machines in the final design, indicating that the students understood the requirement of integrating a number of simple machines to design and build a complex machine. Ways in which the simple machines functioned, including how they interacted in operating the catapult, were noted, although explicit reference to underlying engineering and scientific principles was not always included in their explanations. Nevertheless, the students' descriptions as indicated in the sample responses, revealed an ability to link the physical resources to the abstract concepts being targeted, and an awareness of the design constraints imposed by the resources. Recognition of the importance of collaboration in problem scoping, planning, designing, and constructing the catapult was also apparent.

The need to consider the problem constraints in constructing their catapult was further displayed in the students' evaluation of their design compliance, with most students rating this factor favourably. On the other hand, the limitation of the resources with respect to the sturdiness of their catapult was not rated highly even though the students generally considered their final product to be practical for achieving the problem goal. It would appear that the students were trying to build the "perfect" catapult and assumed that they required quality materials to build their prototype. The students appeared unaware that at this stage of the design process, materials of the best quality are not needed; rather, the purpose of prototypes is to achieve proof of concept and then the actual quality of material selection can be undertaken.

A related finding was that some students were not as satisfied with their efficiency in use of the supplied resources, suggesting an awareness of the imposed problem constraints and how these would need to be taken into account more effectively in future designs. This awareness was further evident in students' responses to improving their design, including more time and a larger budget.

Students' evaluations of the creative nature of their design were varied, with the ways in which they designed their base or combined materials to increase stability and functioning of their catapult being featured. In particular, the use of a pulley system was considered a creative feature of some of the constructions, and was further mentioned as a way to improve the design of the catapult. The mention of comparisons with other groups to evaluate the creativity of their own designs raises a couple of interesting questions worthy of further investigation: How were the students making judgements on the quality of other designs and to what extent were they generating new ideas regarding ways to improve their own design? Providing opportunities for peer assessments and questioning can encourage students to pay closer attention to alternative designs and consider the creative aspects (Enderson & Grant, 2013).

Students were also able to apply their understanding of engineering design and the functioning of simple machines in identifying ways to improve their catapult. All but five students made reference to design features and underlying engineering principles in their explanations. Ideally, had there been more time, the students could have acted on their suggestions and designed an improved catapult, enabling them to further undergo the cyclic processes of modelling and design (Magiera, 2013; Zawojewski et al., 2008). Reflecting on, assessing, and improving ideas as they are developed are critical features of engineering design—processes that apply across disciplines and warrant greater attention in the elementary and middle school curriculum (Brophy et al., 2008; Magiera, 2013).

At the heart of engineering-based problem solving in schools is the teachers' participation in the development and implementation of the learning experiences, with teacher preparation fundamental (Stholmann et al, 2012). The teacher interviews revealed an appreciation of working collaboratively in developing the activities, noting that insights they gained from their peers were valuable in their own classroom implementation. Furthermore, these teachers and their peers in the other schools used their collaborative experiences in refining the activities for implementation beyond the duration of the study. Subsequent networking was a further outcome of the teachers' professional development. These findings suggest that collaboration, with respect to both teacher and student engagement can be a powerful means of advancing learning and an awareness of this learning (cf., Lancor & Schiebel, 2008). A collaborative approach to introducing engineering-based experiences in undergraduate education courses would thus appear to hold promise. Engaging pre-service teachers in engineering design processes as they learn to research, develop, test, refine, and implement classroom activities has the potential to enrich their studies of mathematics and science education.

As a starting point for introducing engineering-based problem solving, we offer an evolving framework that we consider applicable to the middle school as well as undergraduate teacher education in mathematics and science. As shown in Figure 2, our study has taken into consideration a number of components but we acknowledge that there are many other factors within and beyond those we have identified.

We have highlighted design processes as a central feature of engineering-based problem solving, processes

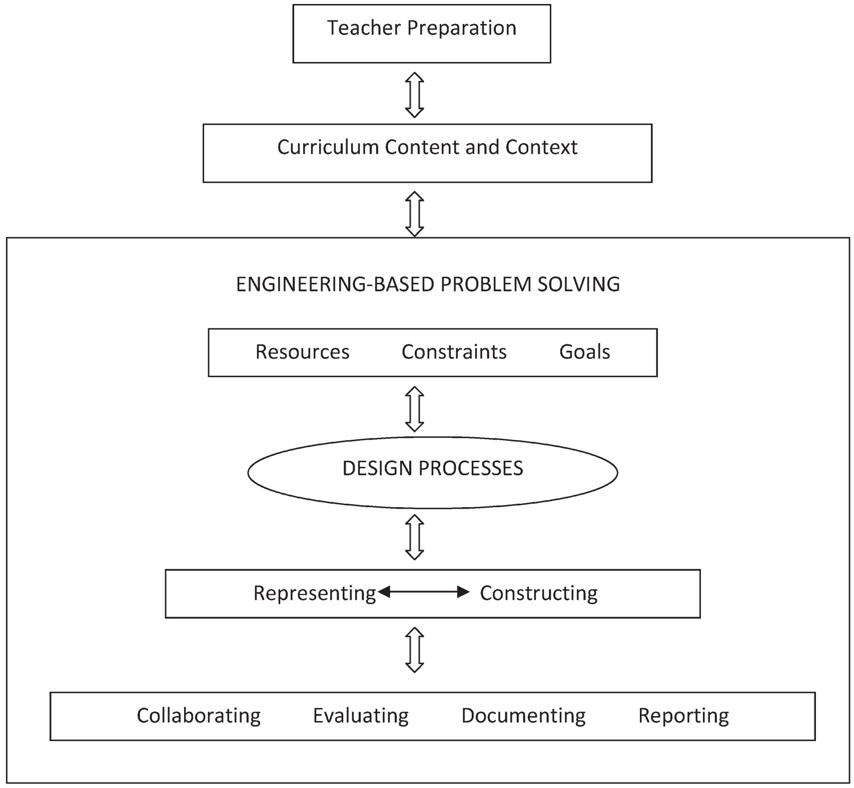

Figure 2. Framework for introducing engineering-based problem solving.

that need to address the resources, constraints, and goals of the problem situation. Although representing and constructing the desired product are part of design processes, we have extracted these features to emphasize the importance of illustrating or modelling what is to be achieved and translating this into an end-product. As indicated in the framework, we consider this a two-way process where students need to compare their intended outcome with what they are actually constructing, and determine whether modifications are needed in one or both. We argue that this translation between representation and construction is a process requiring greater attention across STEM education (c.f., Enderson & Grant, 2013).

The framework also includes a focus on collaborating, evaluating, documenting, and reporting as key elements of engineering-based problem solving. As we have argued, students' constructive collaboration in designing and constructing their product, and evaluating and improving their overall progress towards goal attainment is fundamental. Likewise, students' documentation of their product creation and their sharing of these developments with their class peers are important learning processes across the STEM areas (Magiera, 2013; Stoner et al., 2013).

Concluding Points

Engineering design projects provide engaging experiences for middle school students as well as their teachers. Using engineering as a problem-solving context linking science and mathematics knowledge allows students to design creative and innovative solutions. Solving such problems, however, is a complex endeavour—there are multiple interacting factors that need to be taken into account. Furthermore, students' application of their learning in science and mathematics needs to come to the fore, together with the important links with the targeted engineering understandings. The design of engineering-based problems thus becomes a challenge in itself for teachers and teacher educators. More research is needed on how we can achieve this balance between science and mathematics learning and the development of desired engineering principles. The findings of the National Academy of Engineering's current study, "Toward Integrated STEM Education: Developing Research Agenda," (National Academy of Engineering, n.d.) should provide insights into ways of addressing this issue.

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Appendix

The Catapult Challenge

Design brief for the **Catapult Challenge**: With less than $100 budget, construct a catapult that can be moved by simple machines through the gates (square 30 cm × 30 cm) and up a ramp (10 degree inclined plane and 20 cm long) to a platform. The aim is to then fire a package (projectile) from the catapult as far and accurate as possible.

Constraints for your design include:

1. Size of the catapult
2. Using only the materials outlined
3. Spending less than $100 for the materials
4. All catapults have a projectile of the same mass (one marshmallow)
5. Only simple machines may move the catapult
6. You can test three times and record your results in the Testing Results Table.
7. There must be at least three objective judges for the operation (Judge 1 assesses the accuracy and distance of the throw; Judge 2 ensures the rules are followed; Judge 3 calculates the overall score; Judge 4 ensures fairness of judging). Judges must sign the Best Results Table for your results to count.

Prices	Materials	Prices	Materials
$2	Paddle pop	$2	Cotton reel
$3	Piece of string per 30 cm	$1	Skewer
$3	Rubber band	$0.50	Straw
$3	Dowel	$2	Plastic spoon
$0.50	Plastic-headed thumb tacks	$1	Sticky tape (10 cm)

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