Interdisciplinary Problem Solving: A Focus on Engineering Experiences

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We are facing a serious skills shortage in mathematics, science, and engineering—our efforts to remain globally competitive will be severely hampered if this shortage continues. Numerous recent calls for improving students' learning in these disciplines and for raising our nation's levels of innovation and creativity have been made. In response, this discussion paper argues for a future-oriented interdisciplinary approach to mathematical problem solving, one that draws upon engineering. Consideration is given to engineering as a problem-solving domain, the interdisciplinary knowledge and processes that are fostered, and the role of mathematical modelling in solving engineering-based problems. An example of such a problem for the primary/middle school is analysed.

Worldwide demand for new mathematical solutions to complex problems is unprecedented and has led to an appreciation of the power of cross-disciplinary research within the mathematical sciences and with other disciplines. (National Strategic Review of Mathematical Sciences Research in Australia, December, 2006, www.review.ms.unimelb.edu.au).

Numerous recent reports have highlighted the need to review our teaching of mathematics and science if we are to remain globally competitive. The key findings of the above review alert us to the challenges we face in providing a strong base in the mathematical sciences. Without such a base, "our options for solving complex problems, adding intellectual value to new technologies, spearheading innovation and continuing to compete globally will be severely hampered" (www.review.ms.unimelb.edu.au). In a similar vein, the Business Council of Australia (2007) has argued that, while significant and far-reaching changes have been made in the way the wider community operates and communicates, "many aspects of our school system have not changed since the 1960s" (BCA, 26 Aug., 2007, www.bca.com.au). Of particular concern is the skills shortage facing the Australian workforce. Not surprising, there is a serious skills shortage in the sciences and mathematics, with a predicted estimated shortfall of 19,000 scientists and engineers by 2012 (Department of Education, Science, and Training, 2006).

The above concerns are echoed in the recent call for submissions to *Australia's Innovation Challenge* (Cutler, 2008, www.innovation.gov.au). Cutler has identified seven basic questions for consideration, including the following:

- Can we imagine a better world? Are we asking the right questions?
- Could we do everyday things better?
- How do we educate and equip our people to be creative and innovative, life-long?

The first question addresses the "generation of novel and fresh ideas," which involves "pushing boundaries, and questioning the status quo." The second question focuses attention on creative problem solving "everywhere by everyone," while the last question highlights the need for innovation, creativity, and design to be engendered throughout life. These questions provide grist for exploring ways in which we might advance the teaching and learning of mathematics to address the skills shortages we face.

In this discussion paper I offer one approach to advancing the mathematics curriculum, namely, through interdisciplinary problem solving. In particular, I consider how engineering experiences can enrich the primary and middle school mathematics curriculum by promoting greater student interest in, and appreciation of, mathematics and science in solving real-world problems. Such experiences also help students appreciate how engineering shapes so many facets of our world and how society influences, and is influenced by, engineering. An early introduction to engineering as a career is also a significant component here. I begin by briefly reviewing recent calls for new perspectives on mathematical problem solving.

Calls for New Perspectives on Problem Solving

Research on mathematical problem solving has received a good deal of attention in past decades. Among the notable developments have been Polya's (1945) seminal work on how to solve problems, studies on expert problem solvers (e.g., Anderson, Boyle, & Reiser, 1985), research on teaching problem-solving strategies and heuristics and fostering metacognitive processes (e.g., Charles & Silver, 1988; Lester, Garafalo, & Kroll, 1989), and, more recently, studies on mathematical modelling (e.g., Lesh, in press; English, 2008a). Despite these decades of research, it seems that students' problem-solving abilities still require substantial improvement (Kuehner & Mauch, 2006; Lesh & Zawojewski, 2007; Lester & Kehle, 2003). This current state of affairs has not been helped by the noticeable decline in the amount of problem-solving research that has been conducted in the past decade. As Lester and Kehle (2003) noted, such a decline is not surprising given the increased complexity of problem solving and the multiple categories of interdependent factors that contribute to problem-solving performance.

On the other hand, the decline in this research could also be attributed in part to the mathematics education community's complacency with problem solving, assuming that we know all there is about problem solving and need only refer to established curriculum documents to justify any such research (e.g., *Standards* documents of the National Council of Teachers of Mathematics). Much-needed recent calls for new perspectives regarding the nature of problem solving and its role in the mathematics curriculum have appeared in the literature (English, 2007; Lesh & Zawojewski, 2007; Lester & Kehle, 2003). One such perspective is the interdisciplinary collaboration of researchers in their search for a more comprehensive understanding of human cognition and problem solving (English, 2008b; Lester & Kehle, 2003).

Future-Oriented Interdisciplinary Problem Solving

Future-oriented problem-solving experiences in mathematics and science increasingly require interdisciplinary contexts and approaches (English, 2008b; Lesh, in press). Concerns have been expressed by numerous researchers and employer groups that schools are not giving adequate attention to the understandings and abilities that are needed for success beyond school. For example, potential employees most in demand in mathematics/science related fields are those that can (a) interpret and work effectively with complex systems, (b) function efficiently and communicate meaningfully within diverse teams of specialists, (c) plan, monitor, and assess progress within complex, multi-stage projects, and (d) adapt quickly to continually developing technologies (Lesh, in press). Research indicates that such employees draw effectively on interdisciplinary knowledge in solving problems and communicating their findings. Furthermore, although they draw upon their school learning, these employees do so in a flexible and creative manner, often creating or reconstituting mathematical knowledge to suit the problem situation, unlike the way in which they experienced mathematics in their school days (Gainsburg, 2006; Hamilton, 2007; Lesh, in press; Zawojewski & McCarthy, 2007).

These findings present interesting challenges for mathematics and science educators. For example, how might we help students better understand and appreciate how their mathematics and science learning in school relates to the solving of problems outside of the classroom? How can we broaden students' problem-solving experiences to promote creative and flexible use of mathematical ideas in interdisciplinary contexts? How can we help address the skills shortage in mathematics/science related fields? A promising approach to addressing these questions is through the discipline of engineering.

Engineering as a Problem-Solving Domain

Why should mathematics curricula consider engineering as a problem-solving domain? Australia, along with many other nations, has experienced a significant decline in the number of graduating engineers, an overall poor preparedness for engineering studies in tertiary institutions, and a lack of diverse representation in the field (Dawes & Rasmussen, 2007; Downing, 2006; Lambert, Diefes-Dux, Beck, Duncan, Oware, & Nemeth, 2007). Internationally, the number of Australian engineering graduates per million lags behind most of the other OECD countries (Taylor, 2006). The availability of engineers, mathematicians, and scientists has been identified as "one of the notable competitive disadvantages" for Australia with respect to its level of innovation; Australia remains well behind other nations in this sphere (The World Economic Forum Global Competitiveness Report; http://www.weforum.org).

The need to capture students' interest in the engineering domain before they embark on tertiary education has been highlighted in many recent documents. For example, the Queensland Government's discussion paper, *Towards a 10-year Plan for Science, Technology, Engineering and Mathematics (STEM) Education and Skills in Queensland* (Bligh & Welford, October, 2007) and the *Australian School Science Education National Action Plan 2008-2012* (Goodrum & Rennie, 2007) are illustrative of the increasing concerns being expressed over Australia's need to rebuild engineering and the mathematical sciences.

The proportion of year 12 students studying suitable enabling subjects in mathematics and science has continued to decline at the same time that shortages in engineering domains have emerged (Dawes & Rasmussen, 2007). Furthermore, the representation of women in engineering is still low, despite some efforts at the tertiary level to attract more female students (e.g., Dhanaskar & Medhekar, 2004). More than ever before, we need to increase the profile and relevance of mathematics and science education in solving problems of the real world, and we need to begin this in the primary and middle schools (The Business Council of Australia, 2007). Indeed, the middle school has been identified as a crucial period for either encouraging or discouraging students' participation and interest in mathematics and science (Tafoya, Nguyen, Skokan, & Moskal, 2005). Engineering provides an exceptional context in which to showcase the relevance of students' learning in mathematics and science to dealing with authentic problems meaningful to them in their everyday lives.

The domain of engineering builds on students' curiosity about the natural world, how it functions, and how we interact with the environment, as well as on students' intrinsic interest in designing, building, and dismantling objects in learning how they work (Petroski, 2003). By incorporating engineering problems within the primary and middle school mathematics curriculum, we can: (a) engage students in creative and innovative real-world problem solving involving engineering principles and design processes that build on existing mathematics and science learning; (b) show how students' learning in mathematics and science applies to the solution of real-world problems; (c) improve preparedness of senior subjects; (d) help students appreciate how society influences and is influenced by engineering; and (e) promote group work where students learn to communicate and work collaboratively in solving complex problems (English, Diefes-Dux, Mousoulides, & Duncan, submitted; Zarske, Kotys-Schwartz, Sullivan, & Yowell, 2005).

In summary, given the increasing importance of engineering and its allied fields in shaping our lives, it is imperative that we foster in students an interest and drive to participate in engineering from a young age, increase their awareness of engineering as a career path, and better inform them of the links between engineering and the enabling subjects, mathematics and science.

Interdisciplinary Knowledge and Processes Fostered by Engineering-Based Problems

Engineering-based problem-solving experiences for the primary and middle school need to build on and complement existing core mathematics and science curricula content. Such problems should be designed so that multiple solutions of varying sophistication are possible and students with a range of personal experiences and knowledge can participate (English et al., submitted). *Interdisciplinary knowledge and processes* fostered in solving these problems include the following (adapted from Cunningham & Hester, 2007):

Interdisciplinary knowledge of: (a) what engineering is, what engineers do, and the different fields in which engineers work; (b) core engineering ideas and principles and how these draw upon mathematics and science; (c) the nature of engineering problems and their multiple solutions and approaches; (d) engineering design processes in solving these problems; (d) the role of mathematical models in solving engineering problems; (e) how society influences and is influenced by engineering; and (f) ethical issues in undertaking engineering projects.

Interdisciplinary processes involving: (a) applying engineering design processes; (b) applying mathematics and science learning in engineering; (c) employing creative, innovative, careful, and critical thinking in solving problems; (d) envisioning one's own abilities as an engineer; (e) trouble shooting and learning from failure; and (f) understanding the central role of materials and their properties in engineering solutions.

Mathematical Modelling in Solving Engineering-Based Problems

At the heart of engineering is an understanding of engineering design processes (Cunningham & Hester, 2007) and 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 et al., submitted; Zawojewski, Hjalmarson, Bowman, & Lesh, in press). A basic engineering design process involves the following cyclic components (Cunningham & Hester, 2007). ASK—What is the problem? What have others done? What are the constraints? IMAGINE—What are some possible solutions? Brainstorm ideas. Choose the best one. PLAN—What diagram can we draw to help us here? Make a list of materials needed. CREATE—Follow your plan and create it. Test it out. IMPROVE—Discuss what works, what doesn't, and what could work better. Modify your design to make it better, Test it out.

The cyclic processes of modelling and design (see Figure 1) are very similar: a problem situation is interpreted; initial ideas (initial models, designs) for solving the problem are called on; a fruitful idea is selected and expressed in a testable form; the idea is tested and resultant information is analysed and used to revise (or reject) the idea; the revised (or a new) idea is expressed in testable form; etc. The cyclic process is repeated until the idea (model or design) meets the constraints specified by the problem (Zawojewski et al., in press). Engineering-based problems thus fit very nicely within existing mathematics curricula, in particular, those that incorporate the important strand of models and modelling.

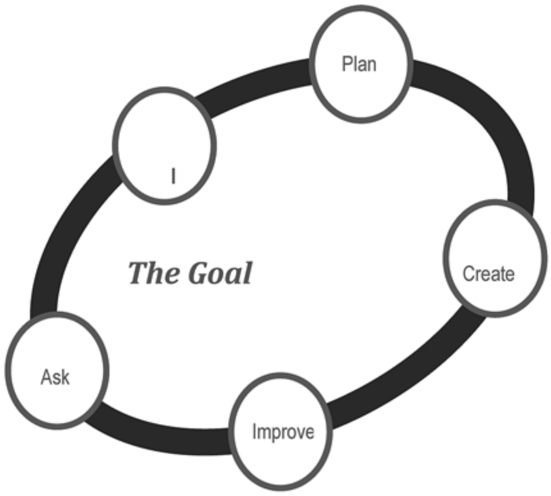

Figure 1. The cyclic processes of modelling and design

Engineering-Based Problem Resources: An Example Exploring Food Packaging

Engineering education in the primary and middle school is a fledging, yet rapidly developing, field of research in the United States, with numerous resources available to teachers and researchers. One of the foremost institutions that are introducing engineering into the primary/middle school mathematics and science curricula is the National Centre for Technological Literacy at the Museum of Science in Boston (Cunningham & Hester, 2007). The Centre's *Engineering is Elementary* program is also being implemented as part of the INSPIRE program at Purdue University (Institute for P-12 Engineering Research and Learning; Diefes-Dux & Duncan, 2007). The Women in Engineering ProActive Network (WEPAN) (www.wepan.org/) has likewise developed sets of rich resources (*Making the Connection*) for introducing hands-on engineering activities to students in year levels 3-12. The goals and activities of these engineering education programs are well suited for integration within primary/middle school mathematics and science curricula and provide fertile ground for interdisciplinary research.

An example of one engineering-based problem from the WEPAN site is "Snack Attack: Food Packaging," the main components of which appear in the appendix (more comprehensive information on the processes of implementation of the problem activities appear on the WEPAN website). This particular problem is targeted at year levels 5-6, but there are several problems addressing this theme for students at other year levels (e.g., for year levels 9 and 10, students redesign and justify the packaging currently used in some consumer products). This hands-on problem activity explores the design process and materials used to package food—students assume the role of an engineer by designing and testing a package for a snack. In doing so, students (a) experience engineering in terms of decisions related to advantages and disadvantages of process and product; (b) identify relevant design features in developing a model to solve a given complex problem; (c) identify materials used to accomplish an engineering problem based on specific properties; (d) rate packaging according to how it performs under test conditions; and (d) consider ways to minimise costs while at the same time produce effective packaging.

An important component of this problem activity is students' sharing of their packaging design model with their peers, who in turn evaluate the models. Significant issues for students to consider here include: (a) the feasibility of the models created and their efficiency (e.g., which ones protect best against heat, water or contaminants?); (b) the amount of packaging used; (c) the cost factors involved; and (d) whether the materials are environmentally friendly.

Follow-up discussions can address the role of mathematical and scientific factors in the decisions companies make on the kinds of packaging materials to use. For example, the size of the packaging, together with the costs and weight of the required materials, bear heavily on decisions made regarding the protection of both the food and the environment. Larger, heavier packaging increases shipping costs. In addition, the more material used, the less environmentally friendly and cost effective the packaging will be.

Charting Research Directions

The theme of this 31st annual MERGA conference is "Navigating Currents and Charting Directions." This paper has highlighted some of the currents we are presently navigating in our efforts to increase participation in key mathematical and scientific domains. As the MERGA website reminds us, "Although we are constantly pushed to account for the quality and impact of our research, we need to assert some control over our work by making our own research futures" (www.addon.edu.au/merga31/welcome.html). Here, I have presented a case for exploring future-oriented interdisciplinary problem solving, one that incorporates engineering-based problems within the primary and middle school mathematics (and science) curriculum. Clearly, substantial research is required to further explore and document the issues that I have raised.

There are several broad avenues of research that need to be investigated here. These include studies that address: (a) the changing nature and role of problem solving in our society; (b) the ways in which problem solving is being addressed in our schools today, including the types of problems presented and the instructional approaches adopted; (c) the ways in which students' problem-solving experiences in mathematics and science can draw upon other disciplines; (d) the developments in primary/middle school students' learning in solving engineering-based problems; (e) the ways in which the nature of engineering and engineering practice can best be made visible to young learners; (f) the types of engineering contexts that are meaningful, engaging, and inspiring for these learners; and (g) the teacher professional development opportunities and supports that are needed to facilitate interdisciplinary problem solving within the curriculum.

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Appendix

Snack Attack: Food Packaging (adapted from WEPAN; www.wepan.org/)

Background

The aim of the problem activity is for students to understand the basic engineering involved in designing food packaging. Packaging engineers have to ensure that food arrives in the best possible condition while using materials that are cost effective as well as environmentally friendly.

Introductory Problem

Snack food has to survive a rigorous journey from its place of manufacture to the point when it is consumed. Discuss how food gets from the manufacturing plant to your home. Brainstorm the different situations food can encounter during transport and the different types of packaging used to protect it. (In addressing this problem, students evaluate the packaging of 3-4 different snack foods such as crackers, chips, and chocolates and document their findings with regard to which materials protect the food from various conditions [e.g., water, breakage, heat]).

Main Problem

A new sweets company wants to package individually wrapped, ready-to-eat snack packs consisting of two squares of cream crackers, a piece of chocolate, and a marshmallow. These packs are often taken on camping trips and are thus subjected to a variety of environmental conditions. After some testing, the condition that the engineers are having most difficulties with is making their packaging WEATHER PROOF. Design a package to protect these snack packs from heat and water. Use the experiment below to help you.

Problem Experiment

Create a package that will keep your snack packs COOL and DRY. The package will need to keep your chocolate and marshmallow from melting during the heat test (45 seconds under a hair dryer on high). Your package will also need to keep your crackers dry when 1 cup of water is poured over it.

RATE YOUR PACKAGE on how well it performs in these two tests, as follows:

Heat Test for Chocolate: Not melted (solid)—10 points; Partly melted—5 points; Completely melted—0 points. *Heat Test for Marshmallow*: No browning—10 points; Partly or completely brown—0 points

Water Test for Cream Crackers: Dry—10 points; Damp—5 points; Wet—0 points

Heat Test for Cream Crackers: Dry—10 points; Damp—5 points; Wet—0 points

The COST OF THE PACKAGING is another concern. Engineers want to design effective packages at the lowest possible cost. You have a budget of $2.00, which means you cannot spend more than this amount on your package but you can spend less. The cost sheet to be completed is below (see Table 1).

Table 1

Supplies to Purchase

Item	Quantity	Amount	Total Cost
Cardboard pieces		40 cents each	
Aluminium foil 15cm square		35 cents each	
Waxed paper 15cm square		20 cents each	
Plastic wrap 15cm long piece		40 cents each	
Small foam plate cut in half		60 cents each	
Toothpicks		5 cents each	
		TOTAL (not more than $2.00)	

Your package will receive a COST RATING from your teacher or the "store manager." The package that costs the least, which is what you want, will get the most points while the package that costs the most will get the lowest number of points. You will then have a total score for your packaging (the results from your heat and water tests plus the results from your packaging costs).