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- book reviews.

Publisher: The Technology, Environmental, Mathematics and Science (TEMS) Education Research Centre, which is part of the Faculty of Education, The University of Waikato, publishes the journal.

Contact details: The Editor, AJTE, pj.williams@waikato.ac.nz

Cover Design: Roger Joyce

This journal provides immediate open access to its content on the principle that making research freely available to the public supports a greater global exchange of knowledge.

ISSN: 2382-2007



australasian journal of **TECHNOLOGY EDUCATION**

Volume 1, 2014

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STEM Education: Authentic Projects which embrace an Integrated Approach

Coral Campbell and Wendy Jobling

Abstract

Science, Technology, Engineering and Mathematics (STEM) education integration is a world-wide response to the falling interest in science and engineering. The approach uses an authentic problem, usually based on a design technology or engineering need, which is solved by school students who apply their knowledge of science, technological design, engineering and mathematics. While there have been different attempts to develop programs that introduce students to a number of STEM concepts in their school curriculum, the practice of STEM integration is not widely used or appreciated.

The researchers present some examples of student projects where authentic learning and integration across the STEM areas is obvious. In Malaysia, the "Search for SEAMEO Young Scientist Congress (SSYS)" is held biennially at the Regional Education Centre for Science and Maths (RECSAM). Middle year students from twelve ASEAN countries present their scientific, technological and mathematical solutions to pressing local and community problems. The projects represent a STEM education approach with the construction of a device or model to illustrate the students' solution. Examples of some of these projects are provided and the discussion highlights the STEM elements, drawing on research into the relationship between science, technology, engineering, mathematics and problem-based learning.

Key words: STEM, integration, authentic learning, knowledge construction

Introduction

Barmby, Kind, and Jones (2008) state that there is a recognised crisis in the provision of scientists and engineers the world over. They comment that the declining interest in science or engineering as a valid career path was being reflected in declining university enrolments. This is mirrored in the number of secondary students engaging with school science in post-compulsory education, raising concern amongst chief stakeholders (educators, government and industry). Loughran, Berry, and Mulhall (2006) comment that a traditional emphasis on teaching science as the transmission of abstract content fails to inspire innovation and creativity. The call for more 'hands-on' teaching approaches in secondary school science and mathematics programs is a direct response to diminishing numbers of secondary students willing to pursue science and mathematics as a career.

Barmby, Kind and Jones (2008) further comment on the importance of scientific knowledge to world economies. Science graduates are necessary for productive industries and for schooling at all levels, but particularly in secondary science. Bevins, Byrne, Brodie and Price (2010) confirm this need for changes to science education, stating that the Confederation of British Industries (CBI) Report (2011) (p. ??) indicated difficulty in finding employees with science, technology, engineering and mathematics skills at all levels.

Similarly, in New Zealand, Cooper, Cowie, and Jones (2010) indicate that the recognition of low engagement in science of secondary students and a corresponding low retention in tertiary science has led to a recent development by the Ministry of Research Technology and Science. The initiative, the New Zealand Science Learning Hub, links research organisations, industries and educators and provides resources to inform teaching.

At the International Conference of Associations for Science Education (ICASE) in 2007, in the *Perth Declaration on Science and Technology Education*, participants expressed concern about the state of science and technology education worldwide, and called on governments to respond to a number of suggestions for establishing the structural conditions for their improved practice. (Austin, 2007, <http://www.icaseonline.net/perth.pdf>).

STEM Education Literature

Diaz and King (2007) suggest that when students ‘do science’, they gain skills such as problem-solving, which help outfit them for future employment. Integrated STEM projects provide students with the opportunity to learn through constructing their own knowledge.

Sanders (2009) defines integrative STEM as: “Integrative STEM education includes approaches that explore teaching and learning between/among any two or more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects” (p. 21).

According to Laboy-Rush (2011), integrated STEM education programs need to attend to the objectives and standards of two or more of the STEM fields.

When teachers expose students early to opportunities to learn math and science in interactive environments that develop communication and collaboration skills, students are more confident and competent in those subjects. This does not only make higher education more attainable for students, but also contributes to a well-prepared society. (p. 3)

So, the intent is to provide students with opportunity to develop and design artefacts through a process of problem-solving.

Integrated STEM education is not meant to replace discipline specific instruction, it is meant to complement it. Integrated STEM projects should engage students’ other discipline learning at the same level. For example, in undertaking a project in Year 9, students would use science, technology, engineering and mathematics knowledge and understandings at Year 9 level.

A recent review of research literature around STEM education indicates that STEM projects work (Becker & Park, 2011). Becker and Park undertook a meta-analysis of a range of STEM research which was published between 1989 and 2009. Overall they were able to study 28 individual projects. The projects used a range of integration connections: Engineering – Mathematics, Engineering-Mathematics-Science-Technology, Engineering-Science, Engineering-Science-Technology, Mathematics-Science, Mathematics-Science-Technology, and Science–Technology. Some projects that were initiated through a mathematics program were less successful than those which used a technology design project or an engineering project. However, the overall analysis of studies from existing research on the effects of integrative processes indicates that there are very positive benefits for student achievement (Becker & Park, 2011). They found that earlier exposure to the integrated STEM suggested improved achievement among students.

Considering the Specific Understandings demonstrated in STEM Education

As many of the STEM approaches place the technological design process as central to the integration of the disciplines, it is important that teachers understand both the technological process and the type of knowledge and skills needed for students to be successful. In particular, a teacher needs to be

sufficiently confident in all disciplines in STEM, to be able to guide the student to the appropriate resources.

Technology

Research by de Vries (2005), has indicated that there is no clear academic equivalent to technology education in other school subjects. He discusses students' need to understand both the aspects of conceptualisation in technology and the role of technology in culture and society. Students need to realise that the technology process, technological knowledge and technological objects are all part of technology. He indicates that in practice, students need to make judgements about effectiveness – the effectiveness of their solution or construction. Students make judgements relating to the function and functioning of their products with respect to the original design brief. In this way, technology knowledge is quite different to science knowledge.

Technological conceptual knowledge aims at understanding how concepts from disciplines such as science apply across a range of biological, mechanical or electrical systems. Barak and Shakkar (2008) comment that there are aspects of knowledge which are unique to technology. The term 'qualitative knowledge' used in technology cognition (taken from McCormick, 2004) refers to the way a person can make evaluations about a technological aspect in a task without needing to understand the underlying mathematics or physics.

Compton (2004) discusses technological knowledge of functionality – that materials or artefacts have a function in which knowledge elements such as detachment, efficacy, longevity, connection and objectivity can be explored. This is supported by research by Meijers and De Vries (2009) which also discusses that in technology there are also certain types of knowledge – knowledge of the function of an item, for example knowing that a hammer is used for inserting nails in wood. Compton defines how tacit knowledge can be recognised in the way a person "knows how" to undertake a task, whilst Barbeiro (2002) recognises that tacit knowledge can be both procedural (knowing how) and conceptual (knowing that – factual). Technological knowledge is frequently complex and tacit.

One other form of tacit knowledge exists in technology education – that of systems. More than just knowledge of how things work, it is the knowledge of how all the components of a system operate together to achieve their purpose. This knowledge enables a technologist to isolate various components to enhance the ability of the artefact to solve the problem or issue (Kelley & Kellam, 2009). "... in short, systems thinking is about synthesising together all the relevant information we have about an object so that we have a sense of it as a whole" (Kay & Foster, 1999, p. 2).

Science

The science demonstrated in STEM education is specifically related to the requirements of the problem-solving task presented, so it is difficult to define with accuracy outside that situation. It may include materials understanding, systems knowledge, mechanical knowledge or any other science area. For STEM to be a meaningful integration, the science involved should be at the level of students' capabilities, that is, of a comparable standard to the science knowledge and understanding that students would acquire in a discipline-specific class. Students having the knowledge to decide on what data are needed, how to design experiments to collect and then analyse (fair testing), e.g. materials for use in the water filter and how these were to be located within the system; undertaking a literature search for reputable scientific papers; and developing knowledge of electrical circuits for the auto trap. Using their project data, they are able to argue their case and substantiate their claims.

Mathematics

It is anticipated that the mathematics' knowledge involved in a STEM project would most often be that of applied mathematics. This could include mathematics of measurement, problem-solving, derivation or determination of formula, or some other aspect related to the task. Like the other

discipline areas, the mathematics must be of a comparable standard to the discipline mathematics being taught. For example: students present collected data in graphical format to assist in the communication of their results (see the mathematics relating to the wind turbine – see Figure 4).

Engineering

The engineering design process is very similar to that of the technology design process. Both include a definition of the problem, an identification of specifications (criteria and constraints), the design or creation of a solution, drawing/building the solution, evaluating the solution (re-design) and communicating results (Arp, 2013 adapted from Engineering [K-5], <http://steps.oregonstate.edu/engineering-k-5>). In some situations, the technological task and the engineering task may be considered one and the same, depending on the viewpoint and prior experience of the person considering the task. For example, each of the cases described later in this paper encapsulate this; the auto trap and the wind turbine in particular.

Research Design

Case studies of students engaging with authentic problem-solving contexts will be presented from the SEAMEO Science Congress. For the congress, students must present their findings from an extended project run within local communities and responding to a community problem or need. Whilst not all projects can be classified as exemplifying STEM integration, many can. The case studies provided in this paper were chosen to illustrate the specific integration of STEM disciplines.

The SEAMEO young scientist awards have been running biennially beginning in 1998 with the 2012 congress being the eighth (the idea was initiated in 1997). Although the themes change subtly from year to year, the overarching focus is on the needs of local communities and sustainability. The rules of the congress encourage students to make use of mentor teachers and university academics (the latter can also give students access to some specialist equipment). Depending on the students' location, this help is variable and in some cases the teacher is the only available mentor. The language used to describe the SEAMEO Congress is very similar to that used to describe a STEM approach. "SSYS aims to encourage young learners to apply scientific and mathematical knowledge into technological problem-solving activities to address sustainable development." (Abdullah, 2012, p. 2).

The congress themes give an authentic context for the problem solving involved and lend themselves to technological solutions. We posit that the technology (design technology) is the driving force in these projects, which the students were so passionate about. Additionally, the students have met a design brief and their application of technological skills and knowledge can be assessed.

In the Science Congress, where many of the projects have a design basis, we can look for the key elements of technological thinking as indicated above. In summary these are:

- making judgements about the effectiveness of their design and solution (requiring both reasoning and critical thinking, problem-solving and awareness of the role of the 'solution' in culture and society);
- consider functionality, purpose, and apply 'qualitative' knowledge which is often tacit (the knowing of how to do a task); and
- systems knowledge.

We can also locate at least one of the other STEM discipline areas (mathematics, science or engineering) as integral to the success of the project.

Presenting the Four Projects

A case study methodology is used to support the development of four cases from the four projects viewed. The researchers were involved in viewing the presentation of each project, reading the final

report and talking with the young scientists (technologists). Yin (2009) states that “Case study research arises out of a distinctive need to understand a complex social phenomena or situation allowing the researchers to retain the holistic and meaningful characteristics of real-life events” (p. 2). Since the description of each project was interpretive in nature, involved a system that was bounded in both time and space, we identified case study as the appropriate methodology.

Case One : Project HF-Autotrap

The HF-Autotrap is a device for catching common household flies. It uses a trapping chamber and a hole at the top of the chamber through which the flies enter. Up to 80 percent of flies which enter will be unable to escape. At the base of the device is a form of lure and a vibrating table which forces air through the trapping chamber and out the hole at the top which, in turn, attracts the flies into the hole. The base of the vibrating platform has an automatic time-delay switch which turns the platform on during the day and off at night. It can be built for household or commercial use. The lure can be made from local waste materials which can be recycled for use at little or no cost.

In developing this device, the students identified the problem of excessive flies near homes and factories which could spread disease. They designed and built three prototypes which were tested by varying different components in an attempt to improve the machine’s effectiveness.

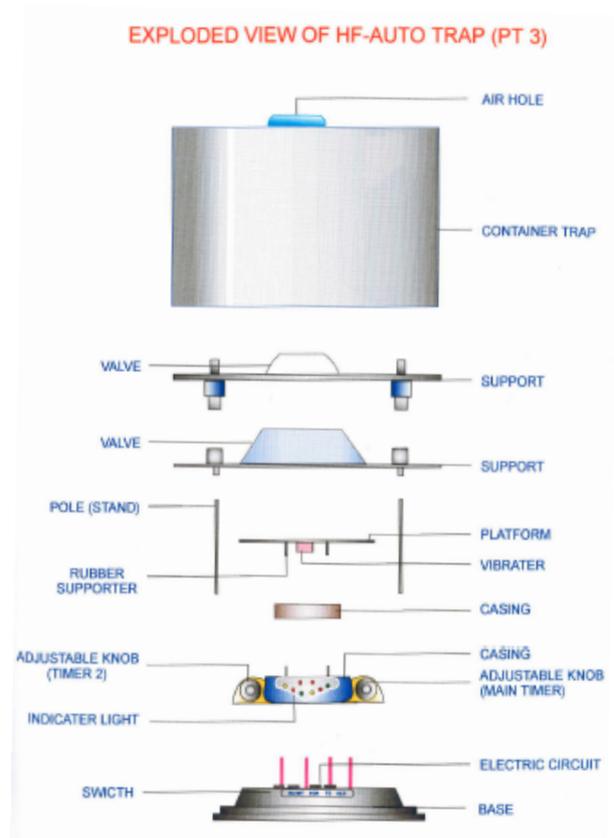


Figure 1:

Exploded view of HF-Auto trap

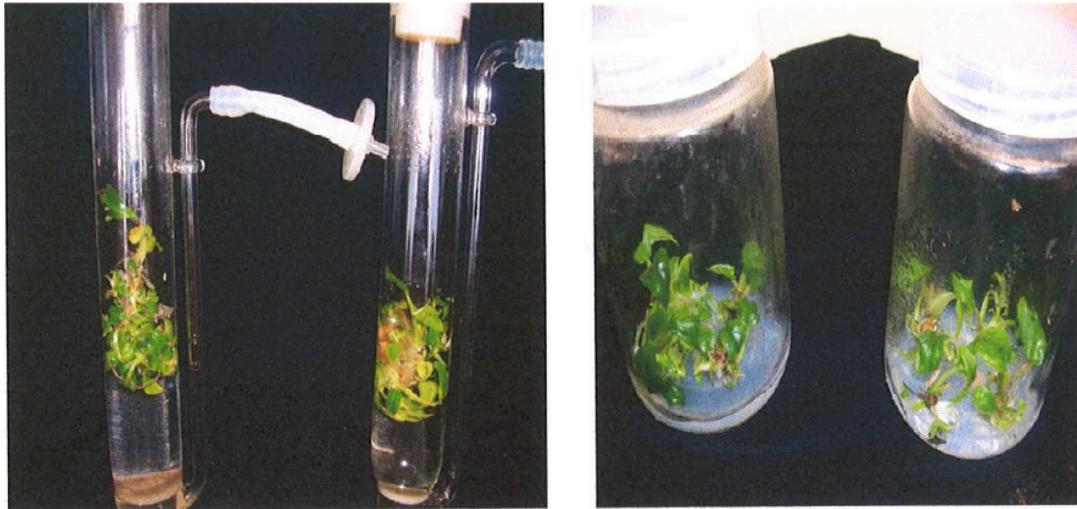
STEM knowledge displayed

The device built highlighted students’ problem-solving skills in systems analysis and in mechanical engineering in the construction of the device. They exhibited systems knowledge and materials knowledge technology (the suitability of the materials for the intended use). Mathematics was used in several ways – both during the construction of each prototype and for recording and analysing data through which evidence can be provided as to which model was the most effective. They understood the idea of functionality and purpose in their design. They displayed an understanding of science (electronics) in the need better use of the design of the switch, and aesthetics appreciation in the symmetry and pleasant appearance of the finished product. Finally, they exhibited an understanding of the role of their solution within a socio-cultural framework. In this case, it is somewhat artificial to break down the task in terms of disciplines as each is important for devising an effective evidence-based solution to the problem.

Case Two: Aerated In Vitro Culture System as a Tool for Rapid Production of Plantlets and Plant Conservation

This was a scientific enquiry into using an aerated *in vitro* system for enhanced plant growth. Students investigated what changes they could make to the rapid multiplication of plantlets to further increase

numbers over a short time. The introduction of air into the standard *in vitro* culture system was one possible investigation. Students already had knowledge of the growth medium used for enhanced growth of the plants and recognised that time limited the number of possible variables they could investigate – hence their selection of an aerated system (possibly suggested by the laboratory they were working with). They learnt the techniques of tissue culture and medium preparation, working in a bio-hazard hood and aseptic techniques to minimise cross contamination. However, at the point of starting the project, they realised that they had a technological problem to be solved. The apparatus required to aerate the plants did not exist. They need to invent it. This required close examination of the existing apparatus and a number of considerations about where air could be introduced into the system. The young scientists had to design their own aeration equipment in glass and have it professionally constructed to be able to complete their science experiments. To design the glassware, the students needed to have an understanding of what they expected their new equipment to do and how it would fit with the other material and equipment in use.



The medium can be used in a variety of containers, including culture tubes and jam jars/ vessels.

Figure 2: Variety of containers which can be used for Aerated In Vitro Culture System.

Technological knowledge displayed

Students displayed strong problem-solving abilities. They had to consider the way their apparatus needed to function so they considered functionality, purpose, and displayed qualitative knowledge - which is the knowing of how to do a task. In being able to design a new aeration system within the apparatus, they demonstrated systems knowledge. As with the first case, the science and design technology are quite clear as is the mathematics in terms of data collection and analysis to check the efficacy of the preferred solution. However, the engineering and the associated science and mathematics are less clear but equally important. Although the young scientists did not have the necessary skills to make the equipment needed, they did need some knowledge of the properties of the glass and how it could be engineered to suit the purpose. The actual application of the science and mathematics to engineer the product was done by the makers they employed.

Case Three: Design of a Wind Power Generator System with Low Wind Speed and Low Cost

The third case examines an authentic need for affordable and accessible electrical energy in small communities. During the 2010 congress, students from Cambodia (Cheng Sophal, Phal Songhak, Norodom Ranarith Kunthabopha, and Hun Sen Saang,2010) presented their solution for solving the

problem of providing small villages with a source of renewable energy for generating electricity (*A Design of Wind Power Generator System with Low Wind Speed and Low Cost.*). Their solution was a low wind speed generator for use in villages not connected to the national grid. Its production involved the use of scrap materials that would be readily available in such communities. The process not only involved the reshaping of materials to form the turbine's blades but also the re-use of parts, such as an alternator from a car, to allow energy storage in a battery.

Although the science knowledge exhibited was impressive, as a technological product to solve a problem it excelled.



The students' use of recycled materials was significant not only in terms of the congress theme but also for if the product is eventually to be made and used by local villagers. These people will need to be able to use local tools to shape the metal as well as have the knowledge to maintain the machine. A small-scale proto-type was presented at the congress allowing the students to demonstrate its use and to explain how it was designed, made and the science principles involved. (There is potential for this model to be used at the village level for a similar demonstration.)

Figure 3: Complete system

Technological knowledge displayed

What can be assessed in terms of technology is the students' knowledge of the properties of materials and how these were considered and influenced the design. This includes the techniques and tools used for shaping and joining. Another area for assessment is how the components are put together to form the system, which is where scientific knowledge is integral. The importance of feedback during each stage of the product's development is vital and can be in the form of the teacher's or mentor's specific questioning as well as peer and self-assessment which help focus students' attention on specific problems to be solved (Black, 2008). As a STEM project, the integrated nature of the task is quite clear and perhaps best shown by Figure 4 below (provided by the student team).

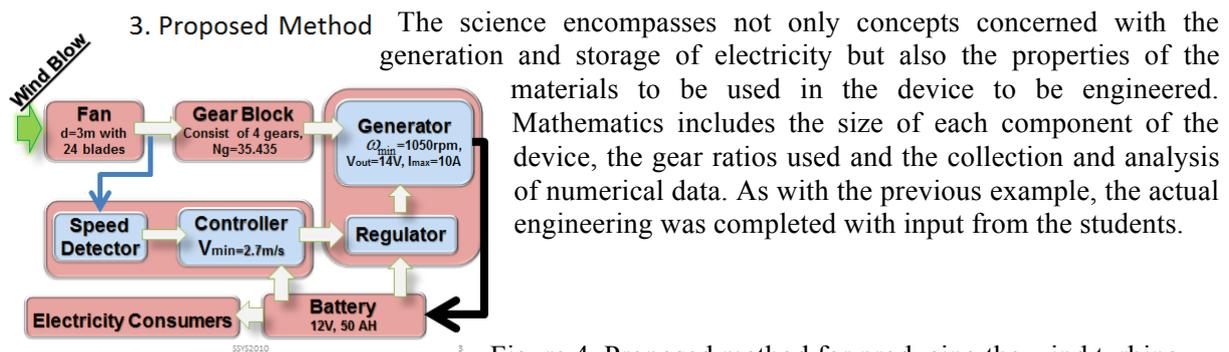


Figure 4. Proposed method for producing the wind turbine

Case Four: Eco filter

The final case is that of a water filter, which the students designed and built to fulfil several authentic needs in the community. The first was the on-going problem of water purity in many villages and rural areas, the second the need for a simple, easily made product to use in the aftermath of natural disasters, and finally as a way in which to educate primary aged students about the excitement of learning science (the students did not think of their project as being in the two areas).



The product designed and made by this team, Jian Zi Poh & Ling En Sheng Joshua (who presented it) was described as an eco-filter. It comprised an outer casing made from discarded mineral water bottles with replaceable compartments. These compartments contained organic matter (Neem leaves, egg shells and husks from rice production). These were to remove heavy metal ions prevalent in most water samples taken from around the island of Penang but also a common problem in many locations throughout the region. Additional materials used to remove large sized impurities were sand and gravels while activated carbon, wood based carbon and volcanic rocks addressed odour removal and colour from the bio-absorbents. The final ingredient to be used was silver-granules to kill bacteria. A feature of this product is the use of predominantly waste materials from agriculture. This makes it low cost as well as readily made by members of local communities.

Figure 5: Model of final product: Eco filter.

Technological knowledge displayed

In terms of what can be assessed with this product are the sources of information used during the investigating phase before designing began

Materials knowledge - Why were the various materials selected for the filter (evidence of their efficacy)?

Systems knowledge - how was the order of their placement decided and what was the evidence for their efficacy (science knowledge integration)?

Problem-solving - What modifications were made during the project and why, and what, if anything, would they change in the future?

Through answering questions such as these the product could be further improved.

Although this device was designed and made with thought given to how it could be manufactured at the village (or even primary school) level, it still integrates each aspect of STEM. The science and design technology are described above with some inferences as to the mathematics – the amount of each material used and the collection and analysis of numerical data to determine the best design. Engineering of the final device taking into account, for example, how it will be put together (including the tap at the bottom) were included.

Conclusion

The four case studies presented promote the value of a STEM approach to learning. The students involved were able to clearly demonstrate their knowledge in all elements of their projects. The technology design process was not apparent in the way the Science Report was written up as the students followed a traditional scientific method approach. However, the design process was obvious within the steps undertaken to solve the problem and arrive at a solution. Students' knowledge in many of the technological thinking skills and ways of operating was demonstrated along with other STEM disciplines. The four examples highlighted thinking related to:

1. The HF- Auto Trap: problem-solving, mechanical engineering, systems thinking and materials knowledge, functionality, purpose aesthetics, socio-cultural awareness, mathematical applications and science knowledge.
2. The aerated *In vitro* culture system: problem-solving, functionality, purpose, qualitative thinking, systems thinking, engineering, mathematics (statistics & analysis) and science knowledge of biology.

3. The renewable energy model: problem-solving, materials knowledge, systems knowledge, mechanical engineering, process knowledge, socio-cultural awareness, mathematics (measurement), and science knowledge (gears).
4. The eco filter: problem-solving, materials knowledge, systems knowledge, socio-cultural awareness, mathematics (measurement and data analysis) and science knowledge of materials.

As indicated previously by de Vries (1996), students often did not require the science knowledge to start their project. The science knowledge developed as they were applying the technological process and technological thinking in attempting to solve their problems. Clearly, in many cases the technology was dominating the science and the mathematics. In future, the integration of Science, Technology, Engineering and Mathematics (STEM) could be one of the evaluation criteria for the projects.

What is clear during the Science Congress is the motivation and interest the students have for their projects and those of others. Authentic problem-based projects, which students seek out for themselves, have proven to not only increase students' interest in science (Mangeo & Cheah, 2013) but provide them with opportunities to engage in real world contexts. Students have been found to have increased scientific literacy, as well as a heightened understanding of the nature of science in the world. The examples we have provided illustrate that the opportunities for a STEM approach are clear and have the potential to assist students with the development of their future technological skills and knowledge of other discipline areas.

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