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STEM education for the twenty-first century: A New Zealand perspective

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Abstract

This paper clarifies the nature of STEM education and how it could fit within the New Zealand Curriculum (NZC) structure. It also considers aspects of course design and adaptations of the National Certificate in Educational Achievement (NCEA) required for successful inclusion within secondary school learning programmes. The paper also discusses some problems and challenges of developing such programmes which require students to interact with, or integrate knowledge from the science, technology, engineering and mathematics learning areas. It finds that rather than replacing established curriculum areas, a STEM course can run parallel to them providing extended learning opportunities for students which are not presently common in New Zealand.

Key Words: STEM Education, course design, senior assessment, integration, interaction.

Introduction

The purpose of this paper is to clarify the nature of STEM education and how it could fit within the *New Zealand Curriculum* (NZC) structure, and adaptations needed for NCEA in order to enable a cross-curricular integrated programme to flourish.

This paper:

- Explains the nature of STEM education;
- Clarifies the place of technology within the STEM cross-curricular approach to teaching and learning;
- Affirms the place of STEM education within the context of the *New Zealand Curriculum*;
- Identifies some key considerations for course design;
- Suggests an important modification needed by the National Certificate for Educational Achievement (NCEA) to support the assessment of a STEM course; and
- Explores a further issue in STEM education that needs careful consideration.

What is 'STEM' Education?

STEM refers to science, technology, engineering and mathematics. Although each individual subject has its own extensive history, the notion of STEM education is relatively new. The commonalities and overlap of subject matter has meant that delineation of each subject area is very difficult. This has led to a combining of subjects such as S&T (science and technology), STS (science, technology and society), TAS (technology as applied science), SET (science, engineering and technology), MST (mathematics, science and technology), and STEAM (science, technology, engineering, art and mathematics). This article discusses STEM.

It should be noted that engineering is generally not a subject that is specifically taught in schools, rather it is situated under the technology umbrella. A useful description of the relationship between engineering and technology is provided by Malpas (cited in Harrison, 2010):

> Technology is an enabling package of knowledge, devices, systems, processes and other technologies, created for a specific purpose. The word technology is used colloquially to describe either a complete system, a capability, or a specific device. Engineering is the knowledge required, and the process applied, to conceive, design, make, build, operate, sustain, recycle or retire, something of significant technical content for a specified purpose - a concept, a model, a product, a device, a process, a system, a technology. (p. 18)

Thus engineering may be seen as an aspect of technology just as physics and chemistry are seen as aspects of science. For the purposes of this article I will include engineering as a subject.

STEM (science, technology, engineering, and mathematics) is commonly used to describe a grouping of key subjects considered important by some politicians, economists, business groups, and educationalists if a nation is to compete in a global economic and scientific world. However, although many countries utilise the STEM acronym, there is little consensus about its meaning. Some people refer to the *multidisciplinary* nature of STEM, and are generally focusing on the four different subject disciplines working independently, while others consider an *interdisciplinary* nature of STEM which focuses on the integration of knowledge and modes of thinking drawn from these four disciplines. Further to this, most people understand what is meant by science, mathematics, and engineering as subject learning areas, internationally there is a wide range of views about what technology education actually is, and what should be included within it (Ritz & Fan, 2014). This article will generally focus on the interdisciplinary nature and opportunities that an integrated STEM learning area might provide for learners, and also describe what technology means within this STEM context.

A traditional silo approach to delivery of curriculum subjects has been common in most secondary schools, although this has not been necessarily so in intermediate and primary schools where integrated (cross-curricular) learning experiences are more common. The notion of STEM education places emphasis on integration of knowledge and skills found in science, technology, engineering and mathematics. The intention is to echo real life where designs and applications are developed by technologists, scientists or engineers who naturally draw on a wide range of integrated knowledge and skills from these different but overlapping knowledge bases. Within a school context, Lee and Granshaw (submitted) suggest that quality STEM education has the potential to enhance success for students in the twenty-first century. It can prepare students for jobs that have yet to be conceptualised by providing life skills such as teamwork, problem solving, lateral thinking, creativity, resilience, and critical thinking. For example, a STEM course design might require students to develop and create a novel solution to a technological problem drawing upon and integrating knowledge from all four STEM subjects. Note that this conception recognises that a STEM course may have a home base in one of the contributing STEM subjects (e.g. it may be based mainly in science), but its design may draw on important content normally taught in one or more of the other subjects (mathematics and technology).

What is Technology?

Science, mathematics and engineering are not new subjects and are conceptually well established, but this is not the case for technology education. There has been, and continues to be, disagreement and confusion over what technology education actually is. This range of views embraces concepts such as design and innovation, product design, intervention by design, and the development of technological literacy. However, it is also understood by some to mean the study of technical and vocational knowledge and skills, and to others, the study and utilisation of computers, computerised equipment and a wide range of digital tools. Technology in *The New Zealand Curriculum* is described as:

> intervention by design: the use of practical and intellectual resources to develop products and systems (technological outcomes) that expand human possibilities by addressing needs and realising opportunities. Adaptation and innovation are at the heart of technological practice. Quality outcomes result from thinking and practices that are informed, critical, and creative. (Ministry of Education, 2007, p. 32)

To eliminate confusion, this article will use the broader and more holistic interpretation of the term *technology education* where the focus is not on gaining or applying technical skills and computing or digital literacy, but rather on thinking creatively to solve design problems which may or may not require these technical skills.

Demands for STEM literacy in the future

There is a wealth of literature available on STEM education and almost all of it agrees that the existing and expanding global economy requires participants with high levels of science, technology, engineering, and mathematical knowledge, now and into the foreseeable future. According to the US Department of Labour there is a need for employees to have knowledge of scientific, engineering and mathematical knowledge and abilities such that they can "read, write and compute proficiently; find and use resources; frame and solve problems; and continually learn new technologies and skills, as well as work in technical occupations" (Asunder, 2012, p. 2). STEM has continued to attract considerable funding in the US, UK, and Australia, since its beginnings in the early 1990s. Over this period of time, STEM has moved from being an initial political agenda, to an implementation of the separate STEM subjects, to an interpretation focusing mainly on the application of science and mathematics with little technology or engineering included, to currently an understanding that emphasises an integrated curriculum programme based on the relationships and interactions between the constituent subjects.

STEM literacy

If STEM literacy is an amalgam of science, technological, engineering, and mathematical literacies, it will be helpful to describe what literacy means in the separate subjects.

Science literacy is described by Dani, (cited in Asunda, 2012) as, "the knowledge and understanding of scientific concepts and processes enabling a person to question, discover, or determine answers to questions derived from a curiosity about everyday experiences" (p. 2). Technological literacy is described as the ability to engage in "intervention by design. It involves the use of practical and intellectual resources to develop products and systems that expand human possibilities by addressing needs and realising opportunities" (Ministry of Education, 2007, p. 32). Engineering literacy requires "an understanding of how individuals, organisations, and society interact at a variety of levels of technology in an engineered world, and how in this process we can exercise meaningful control over the changes that technology creates in our lives" (Heywood, cited in Asunda, 2012, p. 3). Mathematical literacy is described by the Organisation for Economic Cooperation and Development, in Asunda (2012) as:

> an individual's capacity to identify and understand the role that mathematics plays in the world, to make well-founded judgements, and to engage in mathematics in ways that meet the needs of that individual's current and future life as a constructive, concerned and reflective citizen. (p. 3)

STEM literacy, although desirable, has been described as vague and problematic in its form by both Williams (2011) and Sanders (2009), They discuss scientific literacy, technological literacy, and numeracy as being well established and understood concepts, but that this is not the case for STEM literacy. In effect, they argue that STEM education has still not reached the position—a maturity in development—where programmes or courses consistently embed STEM literacy (Williams). In contrast, Bybee (2013) argues that STEM literacy refers to an individual's:

- Knowledge, attitudes and skills to identify questions and problems in life situations, explain the natural and designed world, and draw evidence-based conclusions about STEM-related issues;
- Understanding of the characteristic features of STEM disciplines as forms of human knowledge, inquiry and design;
- Awareness of how STEM disciplines shape our material, intellectual, and cultural environments; and

- Willingness to engage in STEM-related issues and with the ideas of science, technology, engineering and mathematics as a constructive, concerned and reflective citizen. (p. 101)

On a similar tack, Kennedy and Odell (2014) describe STEM education as having:

> … evolved into a meta-discipline, an integrated effort that removes the traditional barriers between these subjects, and instead focuses on innovation and the applied process of designing solutions to complex contextual problems using current tools and technologies. Engaging students in high quality STEM education requires programmes to include rigorous curriculum, instruction, and assessment, [to] integrate technology and engineering into the science and mathematics curriculum, and also [to] promote scientific enquiry and the engineering design process. (p. 246)

If this view of STEM education is to be achieved, all students would need to engage with this type of integrated, cross-curricular education from an early age. This would also require teachers to be supported in developing suitable learning programmes and experiences to allow this to take place.

Affirmation from the *New Zealand Curriculum* (2007)

Support for the development of cross-curricula programmes and courses is clearly documented in *The New Zealand Curriculum* (Ministry of Education, 2007). The NZC requires Boards of Trustees of schools to develop, through their teaching and management staff, a school curriculum that will provide all students from Years 1 to 10 with learning programmes in all eight learning areas. Further to this, "future-focused issues" are considered to be a "rich source of learning opportunities [which] encourage the making of connections across the learning areas" (p. 39). Specifically, the *New Zealand Curriculum* (Ministry of Education, 2007), encourages the development of programmes that make linkages between learning areas:

> While the learning areas are presented as distinct, this should not limit the ways in which schools structure the learning experiences offered to students. All learning should make use of the natural connections that exist between learning areas and that link learning areas to the values and key competencies. (p. 16)

A brief examination of the NZC shows the importance that the Ministry of Education places on the development of programmes of learning for students that include interaction or integration of learning, across and between the learning areas. A well-designed STEM approach, which is based on natural connections between science, technology, engineering and mathematics, will do just that without any major concerns arising about the loss of subject rigour or credibility. A STEM approach to course design should be seen as enhancing learning opportunities and experiences for students in line with the guidance provided by the NZC.

Considerations for course design

A STEM course, as in any other course, should adhere to good course design practice. Hall (2013) suggests that although course design can be approached in different ways, certain elements should normally be addressed. These elements include a clear statement of the purpose/rationale of the course; a specification of the learning objectives that students should demonstrate or achieve; a statement (or mapping) of the course content and sequence; an articulation of the teaching-learning processes (pedagogy) that will be used; a content valid and manageable assessment framework (including formative feedback); and strategies for ongoing and end-point course evaluation.

The first of these elements (a statement of the purpose and rationale) has particular significance for STEM course design. The statement should identify the intention of the course, the justification for developing such a course, the role of each of the individual STEM subjects in contributing to students' learning, and the significance of the integration of STEM subjects for course coherence and overall student learning. A STEM course, by its nature, is likely to involve more than one teacher in its design and delivery. It follows that a common understanding of the purpose and rationale of a course is needed by all participating teachers. STEM education, by its nature, requires teamwork from the different teachers involved. All teachers need to buy in to the purpose and rationale for the course.

The learning objectives of the course should identify the key understandings and skills that students are expected to develop. These will include both specific and integrated STEM subject learning. A statement of the learning objectives need only identify three to six main (intended) outcomes; it is sufficient for these to be broadly worded so that a general sense of direction is provide for all involved—teachers, students and school managers. As an aid, the designers should map out the main components of the course, the contribution of each STEM subject to the course structure and learning, and the significant areas of subject integration or interaction that is expected to take place. In other words, the development of the learning objectives should be well integrated with the specification of the course content and sequence. The development of the learning objectives is likely to be an iterative process; an initial set of objectives may be drafted but these objectives will almost certainly be revisited and revised as course design proceeds. There is always a risk (not just for STEM courses) that learning objectives are treated as precise statements of intent; as noted by Hall (1997), the learning objectives for a course should be treated initially as hypotheses for giving direction to student learning. Over time, as knowledge changes or as different topics or skills become emphasised, the learning objectives will need to be reviewed. Again, teamwork between participating teachers is an important part of the course design.

A particular issue for STEM course design is the need for teachers to identify the knowledge and skills that students are expected to have mastered or learned before they enter the course in question. This may involve obtaining agreement from other teachers (who are not involved in teaching the STEM course) to cover relevant content (e.g. chemical or electrical interactions between different materials may be appropriate science learning, but too time consuming to cover within the STEM course). It may also be possible to support students during a STEM course to obtain important contributing/prerequisite learning by guiding them to external sources (e.g. library or on-line sources) but any such additional learning should not be unreasonable in terms of its workload for students.

Assessment and evaluation are also important elements of the course design process. The next section looks at a particular assessment issue of significance for NCEA. More generally, assessment needs to be connected directly to the learning objectives and course content in such a way that the main assessment tasks that students undertake (there may only be two or three of these for the parts of the course that are internally assessed), require students to demonstrate the ability to relate or integrate knowledge and skills from the contributing STEM subjects. Similarly, evaluation of the effectiveness of the course for supporting students' learning should incorporate a focus on both foundational knowledge (that important content has been understood) and higher learning processes (e.g. problem solving, critical thinking, synthesis of knowledge from different parts of the course). Analyses of student learning should be triangulated with other sources of information, such as student and colleague feedback, and if appropriate, commentary from external stakeholders such as parents, industry representatives if a course has vocational relevance, subject association representatives, and so on. The important point is that a STEM course, by its very nature, is likely to be helping students build intellectual bridges to their future learning and vocational pathways; the use of external feedback is an important component of this bridge building.

Assessment of STEM learning through NCEA

Within New Zealand, the National Certificate for Educational Assessment (NCEA) is the main vehicle for assessing students' school achievement at the senior secondary level. Assessment takes place in years 11, 12 and 13 (corresponding, more or less, to ages 16-18). Each subject is categorised into a number of assessment standards—these vary in number but can be as many as 10 at a particular year level – and schools design courses which embed a subset of these standards. Each standard has a credit weighting (these vary) and a course typically involves 5–6 standards totalling 18–24 credits. Up to three standards in a course are assessed by an external end-of-year examination; exceptions exist, such as Art which is assessed through portfolio submission, and Technology which has some knowledge standards externally assessed by NZQA, while the remainder of standards are internally assessed throughout the year. Moderation procedures exist to monitor grading standards across schools.

Unfortunately, the current design of NCEA presents two problems for STEM education that need to be addressed. Hall (2000, 2005, 2016) has criticised the designers of NCEA for creating a structure that "fragments" course design, teaching and learning. As noted by Hall (2016), the design of NCEA:

> … fosters the breakdown of the curriculum into learning chunks (I have no problem with this), but does not foster anything like as well the knowledge and skills that students need for understanding how the chunks relate to each other.
>
> In other words, the more you break down a subject (course) into separate components for assessment purposes, the more you need to address the assessment of the knowledge and skills that show that students understand the important relationships and connections within the curriculum.
>
> In a high stakes assessment environment, if you don't address through assessment the "integration" of the parts, then the knowledge and skills that underpin the links and connections within and between subjects will be given limited or even no coverage in course design and teaching. This is an example of what is called a backwash effect of assessment on curriculum, teaching and learning. (p. 1)

The argument advanced by Hall is that the design of NCEA has effectively created a defacto modular curriculum, with a strong emphasis on students being trained into passing the standards while in the process important concepts and skills that are not part of the assessment tasks, but associated with the curriculum, become overlooked. In addition, little or no emphasis is given in course design to teaching the connections between the curriculum elements that underpin the assessment standards.

Although not discussed by Hall, there is an associated problem for STEM education. If a school designs a course which crosses traditional subject boundaries, teachers must draw upon existing standards if the assessment of student work is to receive credit for NCEA. Yet the very design of a cross-curriculum course will involve learning that is about the important connections between the contributing subjects. Unfortunately, there are no standards for assessing these relationships unless an existing standard in a subject is fortuitously worded in a way that a teacher can adapt the standard to the course. This absence needs to be addressed in NCEA if cross-curricular courses, such as envisaged by STEM education, are to be encouraged.

A further problem also exists for level 3 (Year 13) NCEA assessment. The current regulations for University Entrance require students to achieve:

- NCEA level 3–80 credits of which 60 must be at level 3;
- Achievement of 14 credits or more in three approved subjects at level 3;
- Achievement of 10 credits at level 2 or above in literacy approved standards; and
- Achievement of 10 credits at level 1 or above in numeracy approved standards.

The second of these criteria effectively reinforces existing subject divisions because it reduces the credits that are available within a course for drawing upon content that lies outside traditional subject boundaries. This again is something that the designers of NCEA need to address if cross-curricula programmes, such as STEM education, are to be encouraged at level 3 of NCEA.

Further issue in STEM education

Whilst integration and collaboration between school subjects sounds an innovative idea, the reality of achieving it may be more complex. A number of issues need to be resolved: the balance of importance between the STEM subjects, particularly in the case of technology, which is a relatively new curriculum area and therefore not as well established and understood as science and mathematics. Technology may be in danger of being undervalued and simply become a means to enhance science and mathematics. Williams (2011) defines the problem "as a technology educator, I would want to ensure the centrality of technology education in a dispositional curriculum, and therein lies the problem" (p. 32) Williams acknowledges that mathematicians scientists and engineers all feel the same about their subjects. He alludes to there being a limited body of research about what an integrated curriculum learning area called STEM actually is and that a STEM approach would have undesirable consequences for technology education:

> In the absence of belief that Technology Education is a fundamental component of general education for all students, a form of STEM integration in which Technology and Engineering serve to enhance the goals of Mathematics and Science may not be perceived as a bad outcome. But for those who believe in the inherent value of Technology Education, its integration with Science and Mathematics would detract from its integrity. (p. 32)

Clearly, all curriculum specialists would consider it vital that the integrity of their areas remain intact. Williams suggests a way forward:

> Interaction is more likely to be locally initiated than integration. Synergies must be identified at times which relate to progression of learning in the subject areas which interact, and the teachers involved must communicate these times of opportunity to each other. For example at the time spatial calculations are being introduced in mathematics, technology education projects could be developed which reinforce the mathematical concepts (architectural drafting): or when materials technology is being applied in technology education (welding ferrous metal), this could be reinforced by studying the nature of materials in science. This type of interaction is facilitated through continual communication between the subject teachers involved, and is limited to the school. (p. 32)

Given the traditional and rigid approach to curriculum, as well as the subject expertise held by most secondary school teachers, it would seem unlikely that radical curriculum reform which involved replacing science, technology and mathematics with any kind of integrated learning programme which allowed students to achieve the essential skills and knowledge of the STEM subjects, is unlikely and undesirable. However, a STEM course which runs alongside the traditional subjects and allows opportunity for students to develop expertise in accessing, synthesising and implementing knowledge and skills from across the STEM subjects is plausible. Seen in this way, a STEM approach could strengthen rather than constrain learning for students and align them with the kind of study common in tertiary education. A further advantage of this kind of parallel curriculum approach is that it not only applies to the STEM subjects, non-engineering subjects such as communications technology, the arts, biotechnology, social sciences and others may be included.

Conclusion

If STEM education programmes and/or learning experiences are to be included within a curricular structure of a secondary school, whether by means of integration or interaction, it will not be enough to simply address STEM aspects within strengthened science and mathematics curriculums as mentioned previously. Awareness needs to be made of STEM as a collaborative learning area which is bigger than its four constituent subjects. For this to gain popularity and traction, learning programmes need to be innovative and exciting for students. The heart of STEM learning is not unlike the heart of technology education in that there is a focus on design and innovation. However, it differs, perhaps, in that the focus of STEM learning by definition needs to be within contexts such as mechanical, structural, chemical, electrical, civil, marine or environmental engineering in order to draw fully upon and integrate knowledge learnt within the STEM subjects.

These programmes need not only provide opportunity to integrate cross-curricular knowledge but also need to foster enquiry learning, problem-solving, and have a project-based structure. A STEM programme or course should be seen as something which enhances or extends present curriculum structures, and not as replacing anything within it.

The implementation of a STEM approach will require teacher professional development in order for teachers to be confident in their planning and delivery. The design of coherent courses, which integrate the learning objectives, course content, assessment and pedagogy, should be given major importance in teacher professional development. The STEM approach will also require adaptations to the NCEA structure in secondary education to accommodate the new integration of learning. This might involve the specification of a generic standard by NZQA that allows schools to add specific information that provides the tailoring needed to deal with the particular integration or interaction that is intended in the course design.

As significant funding is being made available from governments in the US, UK, Australia and elsewhere to explore a STEM education approach and how it might be implemented, it would seem appropriate that further research examines these developments from a New Zealand perspective and that this is from an educational, rather than only from a vocational or economic position.

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