IMPLEMENTING AN INTEGRATED STEM EDUCATION IN SCHOOLS: FIVE KEY QUESTIONS ANSWERED

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This report considers five key questions commonly asked about STEM education:

1. What is STEM education?
2. Why is it important?
3. How do we include STEM in school education?
4. What impact is STEM education likely to have on students?
5. What will be the indicators of success of STEM education?

How do we include STEM education in school education?

Incorporating STEM education in schools needs to happen at three levels: policy, school and teacher. Policy-makers need to acknowledge the intrinsic value of STEM education. Schools should integrate a multidisciplinary curriculum that enables learners to transfer learning across school subjects. Teachers need to work together in learning teams to develop curriculum content and learning activities linked to the external community.

What impact is STEM education likely to have on students?

Impacts should not be confined to academic achievement, but should also consider the social and environmental contexts in which knowledge is gained. Evidence shows that integrated STEM education improves student achievement in STEM discipline areas and in general capabilities such as problem-solving and higher-order thinking. Higher-order thinkers demonstrate nuanced judgement, are able to solve complex problems, live well with uncertainty, are able to self-regulate, can impose meaning on apparent disorder, and are able to elaborate or apply judgement. Students in integrated STEM classes demonstrate increased motivation, improved ability to work together, and positive attitudes to group work.

What will be the indicators of success of STEM education?

In addition to the student outcomes listed above, the success of STEM education can also be measured by teacher professionalism and quality practice. Outcomes for teachers include increased self-efficacy, changes to practice, improved understanding of STEM content and increased pedagogical content knowledge.

The focus of this paper is on STEM education as opposed to STEM. In my work as a science and STEM educator, I have regularly been asked to respond to other educators’ questions about STEM education: What is it? Why is it important? How do we do it? What impact will it have? And how will we know if we have been successful? These are reasonable questions for any professional educator and, while I have provided some insights over the years, I have taken this opportunity to collate the research evidence that provides some answers to these very practical questions. It is my hope that this report can help educators look to the future and provide opportunities for education that is more fit for purpose as we move further into the twenty-first century. We need to challenge the accepted norms of our current education, and STEM education in particular, to prosper in a very different world to the one in which our education institutions were formed.

The five key questions that are addressed in this report are:

1. What is STEM education?
2. Why is it important?
3. How do we include STEM in school education?
4. What impact is STEM education likely to have on students?
5. What will be the indicators of success of STEM education?

A BRIEF COMMENT ON STEM

STEM – science, technology, engineering and mathematics – is not well understood by society, institutions, politicians, or individuals. Many see it as a collection of individual disciplines, each requiring traditional specialization. This is reflected in many policy statements and curriculum policy documents. One review of 222 university STEM staff found that they did not define STEM, but rather talked about the impact of STEM in relation to their work or their children or that it had no impact at all. How professionals define STEM is also reflected in how they talk about their discipline. For example, professional engineers state that the most important professional practice competencies are problem-solving, communication, ethics, lifelong learning, experiments, teams, engineering tools and design. There is no specific reference to STEM in this example, but rather a list of competencies that may be present in the STEM disciplines. Many educators would argue that these competencies also exist in a broad spectrum of disciplines outside STEM.

It is important at this point to define what this report will mean by STEM and by technology. There is wide agreement about what science, mathematics and engineering are as disciplines, but the same cannot be said for technology. In this report, I use a broad definition of technology: “anything that is human made that makes life easier”. Anything that is human made for a particular purpose indicates the inherent connection between design and technology. The current design and technologies curriculum can be viewed as process driven, with an emphasis on developing reflective practice, problem-solving, and self-managed project work. It encourages different modes of thinking and develops metacognitive skills. Design and technologies also draws significantly on maths and science knowledge and processes to inform design decisions and incorporates a discussion of societal values and sustainability as part of its content.
THE STEM WORKFORCE

Many governments around the world, concerned by a leaky pipeline of STEM workers and a progressive attrition from the STEM workforce, have emphasised the economic imperatives of STEM and the need for future STEM workers. Others have questioned the demand for more STEM workers. In 2016, Australia’s Chief Scientist released a report on Australia’s STEM workforce based on the 2011 Australian census. In this report, the STEM workforce data has been updated with the 2016 Australian Census data (see Appendix A: Australia’s STEM Workforce).

Since 2011, there has been a slight increase in the total workforce, and in the percentage of women engaged in STEM, although the latter remains quite low at 17 per cent. Our update shows that the STEM unemployment rate has risen more quickly than the rate for non-STEM unemployment and that the rate of growth in the STEM-qualified population has slowed slightly over the last five years. In Australia’s supply and demand jobs market, these data may indicate a decline in the demand for STEM workers as well as an adequate supply. Other factors, such as the spread of industries and occupations, earning capacity, employment in private or public sector, business ownership and the earning premium of STEM, show little change since 2011.

In addition to the STEM workforce data, this report analyses census data for Australia’s education workforce, that is, people employed in the education and training sector (see Appendix B: Australia’s Education Workforce). It is important to note that the two groups do not overlap. STEM-qualified workers in the education and training sector are not included in the STEM workforce data, even if they are directly involved in STEM education.

From 2011 to 2016 there has been an increase in the total education workforce as well as in the percentage of this workforce who are STEM-qualified women in the STEM workforce. This should be no surprise as research indicates that women are more likely to engage in work that has social benefit. This analysis also shows increases in the proportion of STEM-qualified education workers in the top income bracket over the five years from 2011 to 2016. This increase is greater than that for workers with non-STEM qualifications.

METHODS

In preparing this report, I reviewed some 200 research articles, books and reports in a thematic analysis to address the five questions listed above. I have attempted to provide a balanced view of STEM education research, but acknowledge that the US dominates the research literature in this field. In one review of 798 articles on STEM education, spanning 2000 to 2018, 75 per cent of all publications originated in the US. Australia was second with just five per cent of publications. Overall, the number of papers focusing on STEM education has greatly increased over the past ten years, largely due to the US National Science Foundation’s spotlight on STEM education since the mid-1990s. In other countries, such as the UK, the focus was on SET—science, engineering and technology. When looking more broadly for literature in these fields, there has been some focus since the 1950s, albeit with other acronyms.

WHAT IS STEM EDUCATION?

“What is STEM education?” is a different question to “What is STEM”. The major distinction is that STEM education is for the purpose of learning, while STEM is the practice of professionals in these disciplinary fields. STEM education is not intended to replace learning in each of these disciplines. Rather, it recognises that learning in each of these disciplines is not enough.

“STEM education is an approach to learning that removes the traditional barriers separating the four disciplines and integrates them into real-world rigorous, relevant learning experiences for students.”

This definition highlights three important points: the removal of traditional barriers between these disciplines, the integration of these disciplines, and situating the learning experiences in relevant real-world contexts.

THE REMOVAL OF TRADITIONAL DISCIPLINARY BARRIERS

Each discipline within STEM can be seen as a particular way of thinking and acting. For example, science involves observing, questioning, collecting and analysing empirical data, making inferences, providing justification, generating explanations (often in the form of models and systems), communication and peer review, where experts in the field critically review the work of their colleagues in the same field. What becomes important in STEM education is to explore how science can be applied to real-world problems that require multiple ways of thinking and acting. Such a focus is often known as scientific literacy, where scientific knowledge and skills are used and applied in a range of contexts. The same must be done for all the disciplines. Removing the barriers between the STEM disciplines requires that we remove the traditional siloed approach to learning and engage with the disciplines simultaneously.

Similarly, mathematical literacy contributes “skills in dealing with uncertainty and data [which] are central to making evidence-based decisions involving ethical, economic, and environmental dimensions.”

Engineering contributes to STEM education by:

1. Defining problems by specifying criteria and constraints for acceptable solutions;
2. Generating a number of possible solutions and evaluating these to determine which ones best meet the given problem criteria and constraints; and
3. Optimising the solutions by systematically testing and refining, including overriding less significant features for the more important.

One example of technology’s numerous contributions is through computational thinking. An important part of digital technologies, computational thinking provides opportunities for computational representations to express powerful ideas. It can enhance science and mathematics learning within STEM education, as these disciplines provide rich contexts for computational thinking in a type of reciprocal arrangement that involves data modelling and simulation, problem-solving, and systems thinking.

THE NEED FOR INTEGRATION

Integrating STEM disciplines can take a variety of forms. One can take a holistic approach that links the four disciplines or focus on problems that draw on concepts and procedures from mathematics and science while incorporating the teamwork and design methodology of engineering and technology. All four disciplines do not need to be present all the time, or equally, as the emphasis needs to be on connecting these disciplines to enhance student learning.
For example, observing and gathering data when a proposed design solution is implemented involves science and engineering practices for a distinct purpose. The integration of disciplines in STEM education seeks to locate connections between STEM subjects and provide contexts for learning.

By integrating STEM disciplines, education can focus on skills such as inquiry processes, problem-solving, critical thinking, creativity and innovation, and on developing disciplinary knowledge, through the applied process of designing solutions to complex contextual problems with existing tools and technologies.

Relevance can be generated by combining this understanding with activities likely to be undertaken by students such as cooking (understanding what modifications to a recipe can be made); designing a prototype for a bag, kennel, playground or greenhouse (making decisions about suitable materials); and purchasing goods (lifecycle and lifespan of products).

What is obvious from these examples is that engaging other disciplines is necessary if students are to make sense of their experiences, both within and outside school. In developing capabilities such as creativity, problem-solving and innovation, students learn how these capabilities play out differently in different situations and in different disciplines. Real-world experiences are not located in single disciplines.

“Engaging students in high quality STEM education requires programs to include rigorous curriculum, instruction, and assessment, integrate technology and engineering into the science and mathematics curriculum, and also promotes scientific inquiry and the engineering design process.”

One of the most pressing global challenges facing us at the moment is sustainability. STEM education is a vehicle to explore education for sustainability and sustainable development, that is, “development that meets the needs of the present without compromising the ability of future generations to meet their needs”. Many countries have established sustainability as an educational issue through their national curriculum. For example, sustainability is a cross-curriculum priority in the Australian curriculum.

Increasingly, the purpose of learning science, technology, engineering and mathematics in school is due to the need for a scientifically and technologically literate population. STEM literacy requires individuals to develop the knowledge, attitudes and skills to identify real-world problems; understand the characteristics of STEM subjects; develop an awareness of, and ability to, explain the natural and designed world with this knowledge; and to gain a willingness to engage and reflect upon STEM-related issues as a global citizen. Everyone needs to be STEM literate, not just those in the STEM workforce.

With this in mind, there is an educational imperative for STEM education if we are to respond to global economic challenges. We must recognise that STEM literacy is necessary to solve technological and environmental problems and focus on the knowledge needed to develop the workforce skills required in the twenty-first century.

**WHY IS STEM EDUCATION IMPORTANT?**

**STEM EDUCATION**

In essence, STEM education is the integration of these four disciplines, including their foundational knowledge and a range of skills and competencies that arise when engaging in such disciplines. Although innovation and problem-solving are not unique to the STEM disciplines, they are fundamentally embedded in STEM education.

**STEM EDUCATION AND EDUCATION FOR SUSTAINABILITY**

Education should equip our young people for their futures as citizens in a connected global community. In their school education, students need opportunities to learn in situations that reflect this reality, where what they learn in school will provide them with an understanding of their outside of school experiences.

As a former chemistry teacher, it is obvious to me that learning the particle model of the atom is not going to make much impact on students, nor help them understand their experiences outside of school now or in the future. However, interrogating and understanding the process behind the generation of such a model may be useful. Why were some data excluded and others included? Why were some explanations more reasonable than others? Why is it important to know that matter is made of particles? Engaging in the processes of science generates capabilities in critical thinking (through interrogation) and in the generation of useful explanations and models (a creative process) that can be used to explain other and future events (predictive power).

Establishing why a student needs to know about the particle model is important for understanding how particles rearrange in chemical reactions, how they produce and consume energy, and how their arrangement in structures results in properties such as hardness and elasticity.
In the UK, the government has conceptualised a sustainable development framework based on five principles:

1. Living within environmental limits
2. Ensuring a strong, healthy and just society
3. Achieving a sustainable economy
4. Using sound science responsibly
5. Promoting good governance

All five principles must be meet before any entity, including schools, can be considered sustainable. Meeting these criteria provides an opportunity for schools to address sustainability as both social policy and educational policy. Schools need to consider how they operate (the campus strand), their relationships with local community (the community strand) and their teaching and learning approaches (the curriculum strand). An important education policy here is that accepted structures need to be challenged to determine if they are fit for purpose. Technology and design subjects could take the lead in developing STEM education that includes consideration of sustainable development, for example, energy audits, experiments with different sort of insulation, or building devices to capture energy from renewable sources such as sun or wind.

The current COVID-19 pandemic is another example of the need for STEM education to address global issues through the development of a STEM-literate population. Engaging students in STEM education that is situated in social and cultural contexts, such as climate change or a global pandemic, requires a more interdisciplinary approach to the curriculum. This requires identifying cross-cutting or unifying themes that bridge disciplinary boundaries between subject areas through their explanatory power, and emphasizing the common structure of these disciplines. Both these issues are multi-faceted and will need multiple solutions and approaches. Some mathematical literacy will be needed to understand the representation of data and the subsequent modelling of data that is produced. Both require an understanding of scientific principles to allow a critical evaluation of media representations of these principles, such as which scientist or report has more credibility, to interpret what is known and, equally, what is not known. Both issues will need technological tools to develop solutions such as a vaccine or emissions controls.

Engaging students in STEM education impacts currently held notions of curriculum and conceptions of knowledge and power. Current public perception appears to be that the more discipline-based the subject, the higher its academic status. This perception places considerable power within discipline-based subjects. This power derives from what such knowledge can do or what intellectual power it gives to those who have access to it. But curriculum integration does not mean that disciplinary knowledge is ignored. When students engage with an integrated curriculum, they develop not only content knowledge and disciplinary skills, but also a much broader range of skills such as problem-solving, creativity and argumentation. However, further attention is needed on “assessment practices that can measure authentically what students have learned and how useful or powerful those learning outcomes can be.” Assessment practices, if they are to be authentic, need to measure the more intangible skills such as problem-solving, creativity and argumentation, rather than only the easy-to-measure elements of a narrow band of academic knowledge. Different types of assessment practices, such as formative, diagnostic and summative, will need to be employed.

In responding to global challenges such as those mentioned above, STEM education develops a worldly perspective with two dimensions that can evaluate the power of knowledge and learning. The first is a knowledge dimension, examining the balance between disciplinary knowledge and integrated knowledge. The greater the balance between these knowledge types, the more powerful the knowledge a student develops is likely to be. The second is a locality dimension, a balance between local knowledge and global knowledge. In this dimension, the greater the connection between local and global knowledge, the greater the power of STEM education.

There are three levels to consider when thinking about how to incorporate STEM education in schools: the policy level; the school level, including pedagogical approaches; and the teacher level, particularly professional learning for teachers.

Policy Level

Many countries have policies for STEM education that highlight the economic justification for a future skilled workforce, then use the lack of student achievement in international tests such as the Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA) as evidence for a need to emphasize STEM. Some countries, such as France, Israel and the Netherlands, merge the content of science with technology. Others, such as the US, have developed engineering programs for schools to give context to science, maths and technology. Still others, such as Canada, integrate engineering content into the technology education curriculum or are developing educational models for integrative STEM courses and programs.

For STEM education to be given proper recognition and earn its place in general education, it must have an intrinsic educational value. A similar argument could made for physical education. A healthy population is economically attractive, but the educational value of physical education rests with knowledge about healthy minds and healthy bodies, as well as with the social interactions that come from physical activity. This is why it is included in the curriculum.

The reality is that many countries do not embrace the intrinsic educational value of STEM education in their curriculum policy documents and continue with a predominantly siloed discipline approach. Capabilities such as creativity and critical thinking, or priorities such as sustainability, have been added into curricula with little attention given to how connections between disciplines, capabilities and priorities can be established.

School Level

Individuals do not use knowledge learnt in schools in everyday life and the reverse, bringing learning from everyday life experiences into school, is also true. Learners also do not transfer learning across school subjects – the transfer paradox. The context in which learning occurs (school or everyday life) is critical for understanding and gives meaning to the learning. A multidisciplinary curriculum can begin to address this transfer paradox.

There are three primary factors that significantly affect the success or failure of a multidisciplinary curriculum: a commitment from administrators and teachers to an integration approach; innovation and effort in curriculum redesign; and coordination of the integration plan between administrators and teachers.

Teacher Level

For a school leader, there are several implications of implementing an integrated STEM program as a result of these three factors:

- Effective STEM education requires dedicated, organised and knowledgeable individuals.
- These individuals need to be committed to this approach, rather than waiting for a more traditional option to appear.

HOW DO WE INCLUDE STEM EDUCATION IN SCHOOL EDUCATION?
• While teachers develop their content knowledge, they can focus on quality teaching strategies.

• Schools need to provide time and support for collaboration. Support may include partnerships (for example, with a university or another school or industry), professional learning, common teacher planning time, or encouraging open communication.

• Teachers need to feel that they have the support to be successful.

One fifteen-year study of curriculum integration found several important factors lead to success when integrating STEM:21

• Teachers working together regularly in small and stable learning environments and learning teams;

• Committed and effective leadership, which can come from the principal, a team leader or can be shared between teachers;

• Teacher team activities that are closely linked to the classroom, such as shared curriculum materials, team teaching, collaborative development of themes, or coordination of assessment;

• In-school planning, with dedicated time for teachers to collaborate on facilitated innovation;

• A flexible timetable that establishes the broad structure of curriculum and allows the teaching team responsibility for pedagogical decisions about student groupings, teaching time and space allocation; and

• Curriculum content and classroom activities linked to the external community via both information and action.

Leadership that supports planning, instruction and assessment strategies is vital for the success of all these initiatives and sends a message about what is considered important and what is valued by the school administration. Not all these attributes need to be present all the time. It is the combination of attributes and dedication of teachers that are important determinants of success, along with giving teachers autonomy and control over their work.

Implementing and sustaining an integrated approach to the curriculum can be challenging for teachers, administrators, and others concerned with curriculum reform. These challenges derive from the conflict between a flexible, multidisciplinary, and democratic curriculum and a rigid, disciplinary, and hierarchical school context.22 When measuring learning, it “is important to understand and accept that integrated approaches necessarily incorporate both disciplinary and interdisciplinary objectives, and that the outcomes cannot be assessed authentically with a simple achievement test”.23 These factors focus on the need to build teacher self-efficacy;24 that is, for teachers to feel and believe they are capable of producing the desired effects on students’ learning.

In most schools, STEM education is enacted as ‘StEM’, with science and mathematics seen as more important than technology and engineering. In vocational settings and in life outside school, it is enacted as ‘sTEm’, where science and mathematics support and inform the development of technology and engineering. The latter is more representative of what STEM education needs to be.30

DIFFERENT PEDAGOGICAL APPROACHES TO INTEGRATED STEM EDUCATION

An integrated approach seeks to locate connections between STEM subjects and to provide contexts for learning such content.31 STEM teaching can take various forms and not all disciplines need to be present all the time. However, there is one common feature of all STEM learning: the opportunity for students to apply the skills and knowledge that they have learnt or are learning.9

Developing expertise in pedagogical approaches requires a progression through four steps, from a disciplinary to a transdisciplinary pedagogy.32

1. Disciplinary pedagogy is where students learn concepts and skills separately.

2. Multidisciplinary pedagogy is where students learn concepts and skills separately in each discipline but with reference to a common theme.

3. Interdisciplinary pedagogy is where students learn concepts and skills from two or more disciplines that are tightly linked.

4. Transdisciplinary pedagogy is where students undertake real-world problems or projects that allow them to apply knowledge and skills from two or more disciplines and help shape their own learning experience.

Disciplinary pedagogy

At the least advanced level of STEM pedagogical expertise – disciplinary pedagogy, where disciplines are taught in isolation – there are some improvements to be made. For example, young people’s mathematical learning can be enhanced and extended when activities are designed with four pedagogical affordances: low floors (allowing engagement with minimal disciplinary content); high ceilings (providing opportunities to extend thinking); wide walls (sharing and communicating beyond the classroom walls); and conceptual surprises (students uncovering new ideas).33 These four pedagogical affordances could be applied equally to any of the STEM disciplines in not only a disciplinary pedagogy, but also when considering how to develop multi-, inter- and transdisciplinary approaches.

Multidisciplinary pedagogy

Multidisciplinary pedagogy involves a synchronized approach where specific skills, knowledge, or understandings form part of the content of more than one subject. In this approach, parts of the curriculum are taught separately but simultaneously in different subjects. Teachers identify connection points, explicitly draw links in their classes, and teach them in a similar manner, sometimes using common tasks or assignments.

Another multidisciplinary pedagogy is the thematic approach, which is organized around a local or global topic that enables content of different subjects to be linked (but separate) and often culminates in an event or celebration.

Project-based learning can provide opportunities across multi-, inter-, and transdisciplinary STEM pedagogies. In project-based learning, student teams work together on projects and develop a shared understanding of the subjects and themes. In this learner-centred approach, students are encouraged to integrate knowledge, take responsibility for their own learning, and work in teams to investigate real issues and construct products. Approaches can include more open activities that provide scope for creativity and problem-solving, (for example, designing and developing a household device using electromagnets) or more closed and less creative projects (developing a self-closing magnetic door locking system).

An example of a multidisciplinary, project-based STEM pedagogy is the central project approach. It is a teacher-led approach where teachers (or a team of teachers) integrate STEM subjects around a central activity. The teaching and learning process occurs through both direct instruction, with students taught in separate discipline-based groups, and indirect learning episodes, where students engage in group work to construct their own designs. For example, if the project is about bridge design and engineering, students could learn about stresses and loading in physics classes; in technology classes they could explore design elements based on typical structures; in engineering they...
could learn how to effectively analyse and find fault with the integrity of a bridge’s structure; and in mathematics they could look at load analysis and algorithms for testing different materials and their configurations. Such an approach meets STEM curriculum needs, but pre-selecting the challenge (rather than allowing students to choose their own), reduces student engagement opportunities and focuses on the separateness of disciplines as much as their integration. This leads to a view of integration being seen as an ‘add on’ rather than as the focus of practice.

Interdisciplinary pedagogy

Even when integrating just two disciplines, such as mathematics and science, consideration needs to be given to how students experience, organise and think about science and mathematics.34,35 Overlapping content in mathematics and science provides rich opportunities for interdisciplinary pedagogy. Teachers can take advantage of children’s inherent ability to look for patterns when trying to make sense of the world and adopt instructional strategies that bridge the gap between the classroom and real-life experience. Encouraging students to collect and use data in problem-based activities is important because these activities develop process skills. However, teachers need to be sensitive to students’ feelings and beliefs about science and mathematics, as these elements can affect students’ involvement with, and confidence in, their ability to do science and mathematics.

Studies on effective teaching in mathematics and science have identified the ten most effective practices.36

1. Manipulatives and hands-on learning
2. Cooperative learning
3. Discussion and inquiry
4. Questioning and conjectures
5. Justification of thinking
6. Writing for reflection and problem-solving
7. A problem-solving approach
8. Integrating technology
9. Teacher as facilitator
10. Assessment as part of instruction

While such practices exist widely in schools, they often remain within one specific discipline. These practices tend themselves to integrated STEM education and can build teachers’ confidence in using such practices across disciplines, while also challenging teachers to use these practices in different ways in different learning contexts.

Other types of interdisciplinary pedagogy include a cross-curricular approach based around overarching skills or competencies (literacy/numeracy) or values (environmental responsibility) or social skills (collaboration). This approach cuts across a number of subject areas. Skills are developed in, and applied to, more than one subject at the same time, requiring integration across subjects. For example, ICT integrates skills across design technology, science, mathematics and art.

A school-specialized approach is another interdisciplinary pedagogy. This approach sees a long-term focus on a particular subject area (for example, engineering), with this focus embedded in the whole school curriculum and explicit links in other subjects tailored to this focus.

A community-focused approach is also interdisciplinary but can be transdisciplinary because of the focus on solving a real-life community problem. This approach engages students in an in-depth investigation of a local problem or issue that has significance to the school’s local community. It usually results in some action by the students that has implications for the community.

The Authentic Integration Model37 is another example. This model has four characteristics: knowledge development, synthesis and application; focused inquiry resulting in higher-order learning; application to real-world scenarios; and rich tasks. Each of these characteristics supports the others. The model combines these four characteristics by exploring how knowledge development, synthesis and application, combined with focused inquiry, can support the application of this knowledge and of higher-order thinking skills to real-world scenarios which are, in turn, supported through rich tasks. This model can focus on each discipline or on integrated STEM education and is independent of the inquiry processes and ways of working that apply to particular disciplines.

Exemplars of transdisciplinary, project-based STEM pedagogies include a student-led approach and a hybrid approach that links student projects with curriculum mapping. The student-led project approach gives students a simple design process to follow; then asks them to form teams to design and develop their own project of interest to them.38 The design process will realise a product (for example, a time saving device or an aid for a disabled person) with teachers providing guidance to student teams to help shape their thinking. Students apply a range of concepts relating to STEM, but this content may not always be taught in class. In allowing students to choose their own project, this approach maximises student engagement and also makes them responsible for their own learning. Such an approach, and the wide variety of different projects, presents a significant organisational challenge for schools and requires teachers to monitor each project to ensure STEM curriculum requirements are being met.

In the hybrid project-based STEM pedagogy, students are asked to propose their own design projects and then are assisted to map the learning outcomes they are expected to demonstrate across the STEM disciplines, which is then formalised into a learning agreement.39 The teacher’s role is to negotiate and guide the students’ learning, check-in and monitor their progress, and evaluate the learning progressively.40 Students become more independent and self-directed learners. This approach may provide a challenge for both teachers and students and the increased freedom will also be a challenge for some students. The unstructured nature of the projects may mean that some of the learning outcomes will be difficult for students to demonstrate, and may require several projects across a year for all outcomes to be demonstrated. This approach is the most challenging organisationally, due to the diversity of projects and the wide variety of possible learning outcomes.

Problem-based learning

When engaged in problem-solving, a person is engaged in a complex set of cognitive and metacognitive skills. While some of these skills are shared across the different STEM disciplines, each is unique and often implicitly different within each discipline.40,41,42 This uniqueness is not surprising, as the different problem-solving practices among the STEM disciplines originate in the characteristics of each discipline.43
Problem-based learning is a pedagogical approach that engages students in problem-solving in order to develop these cognitive and metacognitive skills. It has originated in the tertiary education sector and is now beginning to emerge in the school sector.

Problem-based learning is conceptualised as a process involving six core features:19

1. **Learning is student-centred.**
2. **Learning occurs in small student groups.**
3. **A tutor (teacher) is present as a facilitator or guide.**
4. **Authentic problems are presented at the beginning of the learning sequence, before any preparation or study has occurred.**
5. **The problems encountered are used as tools to achieve the required knowledge and the problem-solving skills necessary to eventually solve the problems.**
6. **New information is acquired through self-directed learning.**

Pedagogies that are learner-centred are integral to such approaches to STEM education. In problem-based learning there are fewer ‘whole group’ or ‘teacher-to-many’ interactions – learning occurs in small groups with the teacher as a guide. The role of authenticity has already been mentioned above and is fundamentally important in bridging the gap between school learning and real-world experiences.

The quality of the problem to be solved is central to problem-based learning.203536 Scientific problems can be classified on four dimensions:

1. **Structuredness**
   - Problems that are ill-structured are the most challenging, and therefore present greater opportunities for learning. Ill-structured problems are characterised by poor definition of the challenge, so require analysis to identify the main issue. From this analysis, sub-problems can be determined and prioritised. Outcomes can be examined for evidence of judgement of possible approaches to take in solving each stage of the problem and selecting the most viable approach.

2. **Complexity**
   - Problems should be complex in the breadth and depth of prior knowledge needed and also in the problem elements. Such complexity requires a high cognitive load from learners.

3. **Dynamically**
   - Problems should be dynamic, that is, the variables, and the relationships between variables, change over time.

4. **Discipline specificity**
   - Although problems may not be discipline specific, the different disciplines will rely on different schemas of knowledge and cognitive strategies.53

Given the learner-centredness of problem-based learning, with small groups of students working on solutions to increasingly challenging and complex problems, students need to develop their ability to be self-directed learners. It is important for students, when dealing with complex problems, to understand the breadth and depth of prior knowledge that is necessary and to seek to develop such knowledge.

One model for integrating STEM education that extends this notion of problem-based learning is purposeful design and inquiry pedagogy.54 This model “purposefully combines technological design with scientific inquiry, engaging students or teams of students in scientific inquiry situated in the context of technological problem solving—a robust learning environment... This is problem-based learning that purposefully situates scientific inquiry and the application of mathematics in the context of technological designing/problem solving”.54

Purposeful design and inquiry may provide a mechanism for students who have developed technological design expertise and/or scientific inquiry expertise and can apply this to a technological problem in a collaborative environment. In this way expertise is shared and co-developed and scaffolds how new information can be generated through problem-based learning.

Technology teachers rarely teach science and maths and, while they may use mathematics or science concepts to complete a design challenge, such concepts are not thought of in terms of teaching a desired science or mathematics learning outcome.26 This is an important point, as such approaches to integrated STEM education challenge the assumption that teachers in the STEM disciplines, themselves prepared in conventional ways for conventional settings, are then well prepared to teach STEM education. While these conventionally prepared teachers may produce capable students in science and mathematics, it is well documented that large numbers of students opt out of these subjects.

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**PROFESSIONAL LEARNING**

The above discussion leads to an interesting question: Why would professional teachers, with expertise gained through education and training (in general pedagogy in the case of early childhood and primary teachers and subject-specific content and pedagogical knowledge for secondary teachers) embrace teaching approaches outside their expertise?23 Teachers, as skilled professionals, are being asked to change what they do, even though many of the structures (curriculum, school cultures, and physical environments) in which they practice or were educated still embrace traditional approaches.

Teachers will decide to implement integrated STEM education into their teaching based on a number of factors:253437

- **Curricula – structure and content**
- **Educational trends – current evidence of quality education**
- **Rewards – for teachers and for students**
- **Supports within school contexts – sufficient specific support for such approaches**

**Curricular considerations and educational trends**

Many countries around the world have a siloed curriculum where each discipline is considered separately. Nevertheless, there are some examples, such as Finland, with a phenomenon-based curriculum. In many countries, there is an increasing emphasis on cross-cutting areas of the curriculum – competencies such as creativity, critical thinking, ethical thinking – as well as priorities such as sustainable development. As a result, we are seeing more examples of integrated approaches to studies, even in secondary settings where teachers have specific disciplinary expertise. In early childhood and primary settings, integrated approaches have always existed. However, these integrated approaches are beginning to be marginalised, with increasing emphasis on literacy and numeracy in these earlier years of schooling. Further, in many countries, curriculum integration has previously been seen as a middle school strategy for disengaged students. Now, such integrated approaches are valued for their contribution to a citizenship curriculum that can be embedded in students’ everyday world.28

If integrated STEM education is to become a reality in schools, then there is a need for structural change in the curriculum, with an associated up-skilling of teachers to support this reform.20 To develop integrated STEM experiences for students, there is also a need for teachers and curriculum developers to collaborate and break down the discipline silos.3 Such reform needs to focus on connections and relevance.20 Connections are needed to link what students learn in class with their world outside of school. STEM subjects are needed to provide clever and creative solutions to issues and problems facing our rapidly changing global world. Real-world problems require interdisciplinary teams to work towards solutions and connect schools and students with their communities.

There are discrepancies around the definition of technology in many curricula. Technology can be seen as broad-based (including engineering). It may refer to digital technology, design and/or system thinking-based technology. Engineering is not a discipline in the curriculum in many countries, although the design processes of engineering can be included in science (as in the US) or in design technology (as in Australia). Perhaps an integrated approach to STEM education may solve these issues around the equal representation of single disciplines within the curriculum.

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Implementing any curriculum reform needs to be supported by professional learning for teachers that encourages teachers to be a part of this reform. Professional programs should provide teachers with opportunities to explore their values and should be characterised by questioning, challenging and problem-solving, rather than by a focus on the delivery of a national curriculum.10

**Rewards for teachers**

Rewards for teachers are often intangible and are usually framed in terms of student outcomes or career progression. However, one tangible reward for all teachers lies in the building of self-efficacy through professional learning in integrated STEM education.20 Professional learning programs in STEAM education typically have a set of common characteristics. They increase teachers’ professional knowledge, challenge beliefs, improve classroom practices, and foster student learning and achievement gains.21,22,23 They must be active, sustained, coherent, collaborative, reflective and focused on content knowledge in order to lead to real changes in practice.24,25 They aim to help teachers develop deeper understanding of disciplinary knowledge within the four disciplines of STEM.26,27 Effective professional learning programs explore various mechanisms for integrating content across the four STEM disciplines and develop beliefs and understandings related to integrated STEM education.27,28

Teachers are interested in integrated approaches to STEAM but do not believe they are well prepared for them.29 One study investigating teachers’ beliefs about their ability to teach integrated STEM education involved 135 secondary STEM teachers.30 The researchers explored teachers’ opinions on the relevance and importance of teaching integrated STEM (their professional attitudes), and their feelings of anxiety and perceived self-efficacy when teaching STEM. The study found that teachers’ professional attitudes were influenced by their personal background, their personal attitudes and their school contexts.

Professional learning and development was the only personal background factor that had a positive correlation with teachers’ attitudes towards teaching STEM. There was a negative correlation between teachers’ professional attitudes towards teaching STEM and the personal background factors of having more than 20 years’ experience (teacher attitudes towards teaching STEM were not changed if they had more than 20 years’ experience) and having experience in mathematics – this latter finding is also supported by other studies. A resistance to change among mathematics teachers may be due to these teachers seeing their subject as more self-evident and less related to empirical findings than science teachers.31 Mathematics teachers were also found to help students understand the world outside the classroom less frequently than science teachers. That is, they have less experience with experiments and with involving the class in real-world problems – an integral part of STEM education.

Teachers’ personal attitudes (their attitudes about STEM in their personal lives) were explored through their responses to statements about the perceived relevance of mathematics, science and technology to their everyday lives. STEM teachers’ professional attitudes (their attitudes about teaching integrated STEM) were positively correlated with their personal attitudes and with the personal relevance they saw for science, but this was not the case for mathematics or technology.

School contexts play a greater role in building teachers’ positive attitudes to integrated STEM education than either personal background or personal attitudes.

School contexts were explored through three categories: technical context (technical material, classrooms, budget and technical support by experts); social context (content support by colleagues, effective cooperation with other STEM teachers, a clear vision of the management of STEM education, support by management, professional development in this content area); and organizational context (sufficient teaching hours, small classes and ready-made course material). There was a positive correlation with professional attitudes and the social contexts in which they operate. Such results have also been found by other researchers.32,33

Teachers’ self-efficacy is influenced by their environments and, as seen above, by the social contexts of their specific school environment. Other factors influencing teachers’ self-efficacy also include standardised testing methods and curriculum, social and collegial support, resources (money and materials) and time available within the curriculum.34 Other research has found that teachers’ self-efficacy in teaching integrated STEM can be improved when teachers actively participate in quality professional learning activities,35,36 and when the integrated STEM course is co-taught, so teachers can observe and gain vicarious experience. Teachers with a graduate (masters or equivalent) degree report greater self-efficacy than those with only an undergraduate qualification.37 Self-efficacy increases throughout the early teaching years and into the mid-career years but decreases as teachers enter the later stages of their careers.38 Where teachers have subject-specific experience, for example in physics, engineering, mathematics and technology, their attitudes may be specific to that domain, since tasks and teaching are largely shaped by the nature of the subject being taught.39,40,41

**Supports within school contexts**

Some teachers struggle to implement new, learner-centred approaches to STEM education, even after gaining deeper understanding through professional development programs.42 Such struggles are usually due to barriers or challenges presented within the school context in which the teacher operates. Such challenges include lack of time for collaboration, limited instructional time, and inadequate administrative support and resources. The school’s organisational structure and its culture can also be barriers:43 a testing culture can be a competing value against these pedagogies.44

Advancing STEM education in schools requires more professional learning focused on integrated STEM and the creation of a supportive community for STEM education that includes opportunities to observe and talk with other teachers about effective STEM lessons. STEM teaching is more effective, and student achievement increases, when teachers join forces to develop strong professional learning communities in their schools.45 Effective communities have shared values and goals, collective responsibility, authentic assessment, self-directed reflection, stable settings and strong leadership support.

Schools can promote strong professional learning communities through:

- School staffing policies that create new roles for teachers and support professional learning communities with time, space, embedded professional development, incentives and recognition;
- Policies that engage school leaders in professional learning communities to become knowledgeable and effective team members who help promote initiatives;
- Policies that promote and support the use of online professional networking tools to expand the scope of professional learning communities; and
- Research through professional learning communities on collaborative practices that improve teaching effectiveness and students learning.
WHAT IMPACT IS STEM EDUCATION LIKELY TO HAVE ON STUDENTS?

STEM EDUCATION, STUDENT ACHIEVEMENT AND OTHER BENEFITS

Much of the research exploring STEM education in relation to student achievement considers only the cognitive elements of understanding discipline-based concepts. Such an approach does little to bridge the holistic and philosophical basis for integrated approaches to curriculum and the discipline-based standards on which we judge learning. In other words, there is little attempt to provide and assess integrated education.

An adolescent’s perception of becoming knowledgeable may differ significantly to how schools represent knowledge as discrete subjects. Their view of knowledge and how to obtain it is not confined to a narrow reasoning process, nor is it focused on cognitive gain. It is about the learning that occurs within their social and environmental context. “Gaining knowledge is very clearly about an encounter with the world at this stage of students’ lives.” Therefore, when making judgements about student achievement, we should consider the social and environmental contexts in which the knowledge is gained, as well as the different sources of knowledge, such as teachers, peers, and family members.

A number of research studies support the notion that engaging in integrated STEM education has a positive influence on students’ achievement in both a narrow and in a more holistic sense.

In the US, an analysis of 30 studies on the effects of integrative instruction on student achievement found that students in integrated curriculum programs consistently outperformed students in traditional classes on national standardised tests, in state-wide testing programs and on program-developed assessments. This study also found that integrated curricular programs were successful for teaching science and mathematics across all grade levels, and were especially beneficial for students with below average achievement levels. The third major finding was that studies of science and/or mathematics taught in the context of design improves student achievement, interest, motivation and self-efficacy.

These findings indicate levels of student achievement broadly, across traditional assessments of cognitive knowledge and for students of differing abilities. They have implications for education systems such as Australia’s where there is a regime of standardized tests used to chart students’ progress; where there is evidence of access and equity issues within the system; where there is little encouragement in the curriculum for adopting integrated approaches; and where students are increasingly demonstrating a lack of interest in studying STEM subjects.

A separate analysis of 28 (mostly US) studies exploring seven different types of integration, found similar positive effects on students’ achievement arising from integrated STEM instruction. The greatest effect was seen in elementary schools; the least effect was in colleges. Integration of all four STEM areas demonstrated the largest effect size; the least effect was in engineering and mathematics. It appears from this analysis that, regardless of the type of integration, there are benefits from integrated STEM education.
Authentic learning experiences increase student motivation for learning by situating learning in a meaningful context, and help to build an individual’s identity. Lastly, these experiences improve students’ abilities to retain content by making structural elements, such as roles, communication pathways, expected practices, and socio-cultural contexts, explicit. Elaborating on the point that social interaction is fundamental to cognitive development, it is important to note that the authenticity of the social infrastructures of a learning environment (what structures are present in the school setting to promote the types of social interactions that are experienced in out-of-school settings) are as significant as the cognitive aspects – something that has become obvious in the current COVID-19 pandemic, which has highlighted the importance of schools as social institutions. In such learning environments, there is a need to emphasise collaboration rather than competition if social infrastructures are to support learning. This is particularly the case for women and under-represented groups.

OTHER BENEFITS OF STEM EDUCATION

While some benefits of integrated STEM education, such as increased student motivation and interest, have already been highlighted above, other social benefits have also been identified. One study comparing a grade nine integrated mathematics, science and technology class with classes that taught these three subjects separately found that students in the integrated class gained benefits in their ability to apply shared learning outcomes, their motivation, their ability to work together, and their attitudes to appraisal of group work. The study also found that female students had a better understanding of selected science learning outcomes than their male classmates.

Educators and cognitive scientists have long understood the importance of interest and motivation to learning. Four cognitive themes in particular resonate with integrated STEM education:

1. Learning is a constructive, not a receptive, process.
2. Motivation and beliefs are integral to cognition.
3. Social interaction is fundamental to cognitive development.
4. Knowledge, strategies, and expertise are contextual.

This last point is important. Knowledge and skills are learning outcomes that are tied to the situation and context in which they are experienced and learned. This draws our attention again to the transfer paradox. Learning in a school context is often not transferable. Integrated STEM education provides opportunities to address this paradox through providing learning experiences that are authentic to the context, to the practice of professionals, to a person (including culturally responsive authenticity), and to values held.

WHAT WILL BE THE INDICATORS OF SUCCESS OF STEM EDUCATION?

The success of STEM education will be measured not only by student outcomes, but also by teacher professionalism and quality practice. Although this report has not said much about assessment, it is clear that assessment practices must reflect the proposed learning outcomes, whether this is judging student outcomes or quality teaching.

Students who have successfully engaged in integrated STEM education should be able to demonstrate greater confidence in real-life problem solving and improved team work and communication skills as a result of participating in open-ended problem-solving activities.

“... In the longer term, students will have further developed higher order thinking skills, enabling transfer of learning between subject areas. This might be unconscious (a seamless switching between what they have learnt in different subject areas), or deliberate with the metacognitive super-skill of choosing which mode to think in – as designer, engineer, scientist or mathematician.”

IMPLEMENTING AN INTEGRATED STEM EDUCATION IN SCHOOLS
IMPLEMENTING AN INTEGRATED STEM EDUCATION IN SCHOOLS

Other indicators of success include better student attendance in class as a result of increased student motivation linked to using real-world contexts in which the learning takes place, and the creation of successful student learning teams that adopt practices such as developing expert knowledge and peer teaching.28

OUTCOMES FOR TEACHERS

Successful implementation of integrated STEM education should promote teachers’ professional growth in challenging and supportive ways. It can result in teachers building relationships and working cooperatively to remove artificial learning barriers when developing new programs of instruction. Teachers have the opportunity to engage in creative use of their skills in collaboration with other team members and develop positive team-teaching experiences.29

Other outcomes for teachers include increased self-efficacy, changes to practice, improved understanding of STEM content, and increased pedagogical content knowledge, as has been detailed previously. Important elements that characterize the nature and scope of integrated STEM education are: the type of connections among the STEM disciplines; the disciplinary emphasis or dominant discipline; and the duration, size, and complexity of the initiative (whether it is a single project, single course, curricular program, or entire school).28

Factors that impact on the implementation of integrated STEM education include instructional design; educator support; and adjustments to the learning environment. While the first two of these have been well documented here, the nature of learning environments has been less well documented. However, it is clear that traditional notions of classrooms, with their emphasis on teacher-centred approaches, need significant rethinking. For a comprehensive exploration of what will be needed from learning environments in the future, see the first report in our Education Futures Spotlight Series: “Responsible Innovation: Designing Schools for Tomorrow’s Learners”.106

REFERENCES


FURTHER READING


Australian Bureau of Statistics, Australian Census of Population and Housing 2016, Tablebuilder and Office of the Chief Scientist, Australia
## Education Workforce

### Total Education Workforce

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<tr>
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<th>2016</th>
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<tr>
<td>Women</td>
<td>778,088</td>
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<td>Men</td>
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<tr>
<td>Non-STEM</td>
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<td>STEM</td>
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### Uni vs VET Qualifications in Education Workforce

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<tr>
<td>VET</td>
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### Education Workforce Profile

- **61% Women, 24% Men**
- **39% Non-STEM Qualified, 61% STEM Qualified**

### Income

**Proportion of STEM Qualified in Top Income Bracket ($104K+)**

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<th>STEM = 19%</th>
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<tr>
<td></td>
<td>STEM = 11%</td>
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