United Nations Educational, Scientific and Cultural Organization

International Bureau of Education

In-Progress Reflection No. 30

On *Current and Critical Issues in Curriculum, Learning and Assessment*

Exploring STEM Competences for the 21st Century

Title	Exploring STEM Competences for the 21st Century
Series	Current and Critical Issues in Curriculum, Learning and Assessment
In-Progress Reflection	February, 2019, No.30 IBE/2019/WP/CD/30 REV
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Keywords	Competences – competency-based curriculum – curriculum development – industrial revolution 4.0 – STEM

Exploring STEM Competences for the 21st Century

Abstract:

STEM education seeks to develop and provide innovative solutions to global issues, in particular those directly related to the 2030 Sustainable Development Goals.

As Industrial Revolution 4.0 gains momentum and influences every aspect of our everyday lives, the boundaries between STEM disciplines (Science, Technology, Engineering and Maths) and also between STEM and non-STEM fields, are becoming more and more blurred. Quantum-leaps in technology are forcing us to rethink the way we educate students in STEM and non-STEM fields alike.

The time has come for the education sector to rethink traditional curriculum boundaries, where knowledge and skills are segregated according to subjects. The IBE has led discussions to identify and make explicit the competences that transcend knowledge areas with a view to assisting member states to develop competency-based curricula that prepare young people with the required competences to live sustainable, fulfilled and healthy lives in the rapidly changing world of the 21st century.

There is, currently, limited research into the prerequisite knowledge, skills, attitudes, values and experiences that are a necessary part a competency-based curriculum and also limited consideration of the challenges that teachers face in implementing a competency-based curriculum effectively. This is especially true for Science, Technology, Engineering, and Mathematics (STEM) education, since the concept of STEM as a connected, and potentially integrated, field of study, is relatively new. Accordingly, there is an increasing need for an integrated STEM framework to assist teachers, trainers and curriculum developers to meet the demands for effective 21stC STEM education.

The purpose of this paper is to identify and describe the contributory elements of STEM competence (i.e. the requisite knowledge, skills, attitudes and values) associated with the four core STEM subjects and the potential approaches to teaching STEM that must be considered in order to effectively implement STEM within the curriculum. By highlighting the underlying principles and foundations of each contributory discipline, this paper aims to provide a basis for the development of a STEM competence framework that might helpfully illustrate and enable the coherent and effective integration of a competence-based approach across the STEM field.

Keywords: Competences – competency-based curriculum – curriculum development – industrial revolution 4.0 – STEM

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CHAPTER 1: INTRODUCTION

1.1 The growing importance of STEM

The United Nations' 2030 Agenda for Sustainable Development, entitled "Transforming our World", established 17 Sustainable Development Goals (SDGs)to tackle global issues such as poverty, climate change, food shortage, the protection of the planet; and to ensure that all individuals enjoy peace, prosperity and a quality of life for all.

Education, and particularly Science, Technology, Engineering and Mathematics (STEM) education, plays a crucial role in achieving the SDGs. STEM education seeks to elaborate and provide innovative solutions to solve global issues, in particular those that are directly related to: SDG 2 (Zero Hunger); SDG 3 (Good Health and Well-Being); SDG 6 (Clean Water and Sanitation); SDG 7 (Affordable and Clean Energy); SDG 9 (Industry, Innovation and Infrastructure); SDG 12 (Responsible Consumption and Production); SDG 13 (Climate Action); SDG 14 (Life Below Water); and SDG 15 (Life on Land). Moreover, SDG 8 (Decent Work and Economic Growth) and SDG 11 (Sustainable Cities and Communities) are heavily dependent on progress that can be made within the fields of STEM. In the context of Industry 4.0, the contribution of STEM to achieve the SDGs is crucial (UNDP, 2019).

It is widely agreed that solutions to the challenges that the world faces today will require a new multidisciplinary scientific workforce equipped with a skill set of new technology and interdisciplinary thinking that may "require the integration of multiple STEM concepts to solve them" (Wang, Moore, Roehrig, & Park, 2011, p. 1). It is also widely agreed that there is an imperative to train and prepare a diverse STEM-literate workforce with the capability to understand and comprehend the technological world (Merchant & Khanbilvardi, 2011).

1.2 Purpose of this paper

Since the concept of STEM as a connected, and potentially integrated, field of study is relatively new, there is, as yet, a lack of consensus related to the details of STEM integration. Accordingly, both national and international policymakers are advocating a STEM agenda. In a climate that is increasingly embracing STEM concepts in the workplace, greater literacy in these disciplines, and how they relate to each other, is imperative.

Yet, despite the demand for a new generation of STEM experts and the massive increase in focus on STEM education reforms over the past two decades, there has been a limited amount of research to identify the prerequisite knowledge, skills, attitudes, values and experiences that constitute competence in STEM and the challenges that teachers face in implementing STEM effectively.

The purpose of this paper is to identify and describe the elements of STEM competence (i.e. the requisite knowledge, skills, attitudes and values) associated with the four contributory STEM subjects and the potential approaches to teaching STEM that must be considered in order to effectively implement it within the curriculum. By understanding the underlying principles and foundations of each contributory discipline, this paper aims to provide a basis for the development of a STEM competence framework that could better illustrate the interdependencies and potential for greater integration across the STEM field.

1.3 What is STEM?

The core feature of STEM is the use of science, mathematical, technical, engineering knowledge to solve daily or societal problems, making the learning of science, technology, engineering and mathematics more meaningful and contextual. STEM literacy has been defined as:

- Knowledge, attitudes, skills [and values] 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 with the ideas of science, technology, engineering, and mathematics as a constructive, concerned and reflective citizen.

Bybee (2013, P5.)

However, different conceptions of what STEM means in practice often depend on the perspective from which it is viewed within the education system. Many think of STEM as four separate disciplines. Others consider STEM to be an integration of two, three or all four disciplines. The aspiration of avid advocates of STEM is that practice should embrace an interdisciplinary teaching approach, which removes the learning and development barriers between the four disciplines of Science, Technology, Engineering and Mathematics. While each of the disciples has its own history, philosophy, and principles and its own distinct reservoir of knowledge, skills, and functions, nevertheless, advocates consider that bringing the four disciplines together, as STEM, is theoretically sound and valid, since science and mathematics are generally considered to form the basis of applied science, which includes technology and engineering.

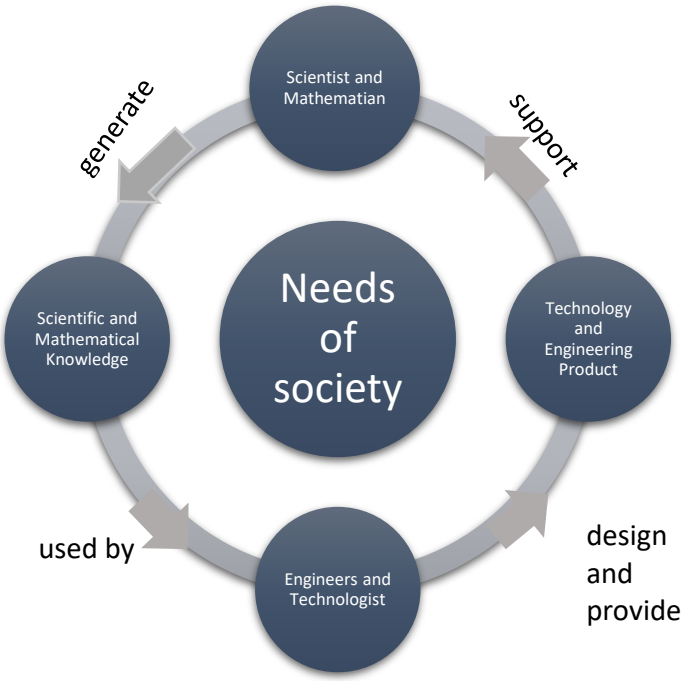
The alignment of these four established disciplines into the entity now known as STEM was first proposed in the 1990s by the US National Science Foundation, to address a rising concern that many students would not be able to keep up with, and might even be left behind, in the globally competitive marketplace guided by an increasing demand for STEM related skills and

competencies (Vasquez, 2015). There was also a concern in some parts of the world about a decline in young people' involvement in STEM fields at schools, universities and colleges and throughout their careers (Milner et al., 1987; Aina and Akanbi, 2013; Bahaar and Adiguzel, 2016; Sithole et al., 2017). This decline in motivation to engage with STEM was partially attributed to outmoded content, poor pedagogy and a lack of applicability to real contexts, resulting in students not being able to relate the knowledge they acquired in school to real life challenges and their future careers (Milner et al., 1987; Aina and Akanbi, 2013; Bahaar and Adiguzel, 2016; Sithole et al., 2017).

The aim of taking an integrated or interdisciplinary approach to STEM is to advance and synergize the efforts to equip students with a sturdy theoretical foundation that will enable them to propose innovative solutions to the problems of the society and the world.

Figure 1 demonstrates how the four components of STEM - science, technology, engineering and mathematics – work together towards fulfilling societal needs and aspirations.

Figure 1: Relationship between Components of STEM



1.4 Historical background

The STEM acronym is not entirely new. Ancient Greeks, such as Hippocrates and Aristotle, had begun to delve into the study of things in their environments, giving rise to the field of science. The study of mathematics as a demonstrative discipline began in the 6th century BC with the Pythagoreans. Engineering, which entails the design, construction and operation of machines,

systems and processes based on scientific and mathematical methods, has existed since ancient times when humans devised inventions such as wedges and pulleys. Millions-year-old stone techniques and tools mark the beginning of the history of technology.

The four Industrial Revolutions (IRs) have resulted in gigantic leaps in industrial development which, in turn, have had a massive impact on human civilization and the way we live our lives. The first IR of the 18thcentury introduced the steam engine, which completely transformed the transportation and manufacturing sectors. The second IR in the 19th century heralded the introduction of electricity and mass production. The third IR of the 20th century brought with it semiconductors, computing and the use of internet, which have helped to connect the world and globalize communication and trade.

The current era of the 4th IR is a time of unprecedented invention and rapidly emerging technological breakthroughs, which has hastened the digital revolution and the fusion of technologies that transcend and blur the boundaries between the physical, digital and biological spheres. Many seemingly 'unthinkable' emerging technologies are changing our daily lives including, among others, the fields of robotics, artificial intelligence, the Internet of things, 3D printing, autonomous vehicles, quantum computing and nanotechnology. Already the 4th IR is changing the way we understand the production of goods and services, as well as the management of business. These innovations collectively, have repositioned the importance of STEM and the role of STEM competences in contributing to economic growth, productivity and meeting future demand.

The role of human beings in the work setting has also shifted. The demand for STEM manpower is no longer reserved to leadership and professional positions such as scientists, engineers, and mathematician; It has expanded not only to include qualified technicians and a wide range of skilled workers with STEM competencies. The demand for STEM competence now extends to areas such as advanced manufacturing, utilities, transportation, mining, and other technology-driven industries. On the one hand, while technological change across these industries reduces overall employment. On the other hand, it has increased demand for highly skilled workers with STEM competences, which are now regarded as critical for innovation and for creating a competitive edge in knowledge-intensive economies.

STEM knowledge has evolved since the 18th century in line with the expansion, diversification and specialization of science into the fields of physics, biology, chemistry, applied science, mathematics. Over the last two decades, some fields have integrated or fused within higher education to create a new discipline, e.g. that of biology and chemistry giving rise to biochemistry.

This development, however, has not occurred within schools. The school curriculum as a programme of learning with specific objectives, content, pedagogical methodologies and methods of assessment, is geared primarily to preparing students for further and higher

education and, to a lesser extent, the workplace. Indeed, one of the major challenges that schools' science and mathematics curricula face is that universities and workplaces still consider the traditional subjects of physics, chemistry, biology, science and mathematics as the channels through which students are able to enrol into tertiary STEM courses or apply for STEM-related jobs. Meanwhile, the relevance of single, segregated subjects is being called into question as awareness grows that the competences to address and resolve contemporary issues, such as sustainable development, require a cross-disciplinary approach.

It is now increasingly recognised that educational policy, educational programmes and curriculum need to be futuristic, in the sense of preparing future workers, leaders and citizens to work innovatively and flexibility to respond to the challenges they will face throughout their lives at a local and global level. There is always a need to look ahead, to try to predict what may be needed in the future to meet the visions of each community and country. As the world faces the surge of innovation associated the 4th IR, during which STEM is anticipated to dominate development and progress on a global scale, it is crucial for all governments to consider integrating the philosophy of STEM into their national education blueprints and plans, as well as their national curriculum framework.

A STEM philosophy consists of understanding the relationship between the various disciplines of STEM, what STEM competence entails, and the purpose and role of STEM education in nation building. It is thus important for curriculum developers to consider cross-disciplinary concepts and approaches as well as to acknowledge the specificities and characteristics of each STEM discipline. For example, the US National Research Council (2012) advocates that STEM knowledge includes both several discipline-specific core ideas and cross-disciplinary concepts which students need to learn from kindergarten through secondary schooling and into further and higher education and the workplace.

The acknowledged objective of STEM education is to develop well-informed and highly competent citizens in the age of the 4th IR. Some researchers draw attention to the idea that STEM is a socially constructed discourse that is responsive to society, and deploys efforts to deconstruct existing social inequities. STEM is thus considered as instrumental to ensure a fair, inclusive and harmonized society (Chesky and Wolfmeyer, 2015; Ritter, 2017). Thus, all countries need to identify specific STEM competences that their citizens should acquire, not only to meet future labour market demands, but also to ensure a sustainable and quality of life for all. The following chapters explore and discuss the knowledge, skills and attitudes related to STEM with a view to informing a specific STEM framework that links to generic competences for the 21stC and the 4th Industrial Revolution.

CHAPTER 2: THE COMPONENTS OF STEM COMPETENCE

2.1 What is STEM competence?

Competence is defined by the IBE as 'the developmental capacity to interactively mobilise and ethically use knowledge skills, values, attitudes and technology to engage and act effectively across 21st century contexts to attain individual, collective and global good (Marope 2018).

In a fast-changing world, with technology evolving at an unprecedented pace, competence is conceptualised as a developmental capacity rather than as a set of fixed skills (Marope, 2017). Based on these definitions, STEM competence refers to an individual's ability to apply STEM knowledge, skills and attitude appropriately in his or her everyday life, workplace or educational context. It should not be confined and developed within the traditional boundaries of discrete bodies of knowledge (e.g. physics competence or computing competence).

STEM competence covers both the 'know-what' (the knowledge, attitudes and values associated with the disciplines) and the 'know-how' (the skills to apply that knowledge, taking account of ethical attitudes and values in order to act appropriately and effectively in a given context). In the information age of the 4th Industrial Revolution, the 'know-what' and the 'know-how' of STEM encompasses the traditional components of knowledge, skills, values and attitudes and the all-important expansion of information, big data and technology. It is important not to view these components as isolated or 'stand-alone', but rather, in a connected, contextualized and holistic manner. For instance, in an educational and work context, students need to interact and explore the different elements of technology, skills and appropriate values in order to 'act' to solve problems and make decisions.

The various components that comprise STEM competence, therefore, need to be integrated into students' learning processes to enable and encourage students to engage with issues and become more reflective in addressing societal challenges. A worker with STEM competence is able to use STEM knowledge, skills and attitude effectively to carry out technical or professional tasks. Equally, a citizen with STEM competence is empowered to enhance his or her life on a daily basis, while contributing to the fair, inclusive and holistic development of his/her country and the world.

The following sections delve further into the component elements of STEM competences, involving knowledge, skills, attitudes and values, which interconnect and combine to inform effective STEM thinking and actions.

2.2 STEM Knowledge

STEM knowledge includes epistemological knowledge, procedural knowledge and technical knowledge associated with each contributory STEM discipline and how associated ideas, concepts, principles and theories overlap and interrelate. Procedural knowledge provides the foundation for the acquisition, application and practice of STEM skills such as measuring data, ascertaining its' precision, validity and reliability, as well as selecting and displaying it. Procedural knowledge is developed through investigative and hands-on activities in and outside the classrooms. It should be done in a progressive and dynamic way, to ensure that students keep up with the latest developments. Equipping students with procedural knowledge enables them to explore and subsequently explore STEM principles and applications by themselves. Technical knowledge is related to the application of knowledge, skills, attitudes and values to a specific field, career or task, such as civil engineering.

2.2.1 Big ideas

Big ideas form the building blocks of any field of study. A big idea is a concept or statement that is central to the learning of the particular discipline/field, one that links diverse elements of understanding into a coherent whole that is representative of the discipline/field (Randall and Carmel, 2005).

Big ideas are also ideas applicable across different disciplinary subjects. In other words, big ideas are often cross-cutting concepts (NGSS Lead States, 2013a) that are like lenses through which we view and make sense of the world around us (Harlen 2010, 2015).

Teachers need to continually connect and relate learning content to big ideas, reinforcing them throughout the lessons so that learning becomes coherent, meaningful and impactful. By making connections between big ideas, and subsequently extrapolating these connections within the same field or to other fields, students develop their respective foundational understanding of the discipline/field. The number and strength of these connections are indicators of their level of understanding. Through the formation of learning webs, students will no longer view the discipline or field as a set of disconnected concepts, skills and facts, but rather as a coherent body of more meaningful knowledge (Randall and Carmel, 2005). Thus, it is important for curriculum developers and teachers to identify the big ideas that ensure curriculum coherence.

Big ideas have received considerable attention within science education. In fact, lists of big ideas of basic science and mathematics have been established (see Appendix 1 and Appendix 2 respectively) and every subfield of science such as chemistry and physics has its own list of big ideas (Harlen, 2010, 2015; Randall, 2005). Big ideas in engineering emanate from the need to promote engineering as a people-focused, problem solving, and socially beneficial discipline. They focus on engineering habits of mind, including systems thinking, creative problem solving,

problem finding and adapting, improving and visualising. See Appendix 4 for the big ideas associated with engineering thinking. (Royal Academy of Engineering, 2014; Institution of Mechanical Engineers, 2016).

2.2.2 Big ideas across STEM subjects

STEM is an accumulation of the knowledge components of science, mathematics, engineering and technology, which have become inextricably linked. The need for big or core ideas in STEM is two-fold. The first is pragmatic: in the face of rapid scientific advancement there is a need to make chunks of scientific and mathematical facts and theories into a more meaningful and manageable whole. Secondly, integrated STEM activities allow teachers to focus on big ideas that are connected or interrelated between subjects (Stohlmann et al. 2012). Two examples of how big ideas in STEM have been framed have been put forward by the National Research Council (NRC) in the United States and the International Baccalaureate Organization.

The United States National Research Council (NRC) has organised their conception of the core disciplinary big ideas of STEM as follows:

Table 1: Big Ideas in NRC

Big Ideas (made up of Cross-cutting concepts)	Explanation
Patterns	Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.
Cause and effect	Mechanism and explanation. Events have causes, sometimes simple, sometimes multi-faceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.
Scale, proportion and quantity	In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.
Systems and systems models	Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.

Big Ideas (made up of Cross-cutting concepts)	Explanation
Energy and matter	Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.
Structure and function	The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.
Stability and change	For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.

Source: National Research Council, 2012, p. 84.

These core big ideas are organised into four domains: 1) physical sciences, 2) life sciences, 3) earth and space sciences and engineering, 4) technology and applications of science (NRC, 2012; NGSS Lead States, 2013a, 2013b) and are spread over multiple grades from primary school to high school, to form *Next Generation Science Standards (NGSS)* which are outlined at each grade with an increasing level of depth and sophistication. When putting together the big ideas of STEM, NGSS therefore has continued to recognise the traditional areas of studies such as physical science and life sciences and the NGSS highlights the importance of making these cross-cutting concepts explicit to students. Its main objective is to provide an organizational schema to draw and combine knowledge from various STEM fields into a coherent and scientifically-based view of the world (NGSS Lead States, 2013a).

Another example of how to approach STEM in an integrated way is outlined within the *Middle Years Programme International Baccalaureate (MYPIB)*, a globally recognized secondary school programme, based on a curriculum framework that lists a set of relevant cross-cutting concepts or 'big ideas' that are relevant within and across disciplines and subjects.

The MYPIB focuses on concept-based learning where similar concepts are shared and diffused between different disciplines/subjects. Such interdisciplinary learning is a compulsory feature in MYPIB. Students encounter cross-cutting concepts through various subjects simultaneously (International Baccalaureate Organization, 2015a, 2015b). Students are encouraged to be aware of these concepts through learning activities in various subjects. They use these key concepts to inquire into issues and ideas of personal, local and global significance. Understanding these key concepts is instrumental in assisting students to develop principles, generalisations, and theories of the subject matter (International Baccalaureate Organization, 2015a, 2015b).

Students learn to relate to these cross-cutting concepts through two forms: key concepts and related concepts. As students learn to make connections between these cross-cutting concepts and experiences, they acquire rich understandings about the different forms of knowledge encountered (International Baccalaureate Organization, 2015a, 2015b). Tables 2 and 3 (below) provide examples of key concepts and related concepts in the domain of science within the International Baccalaureate.

Table 2: Key concepts in Science within the *Middle Years Programme International Baccalaureate*

Key concepts	Explanation
Change	A conversion/shift/movement from one state to another, Exploring change allows students to examine forces that shape the world: past, present and future. Inquiry into the concept of change invites students to consider causes, processes and consequences: natural and artificial, intentional and unintentional, positive and negative.
Relationships	The idea of relationship allows students to identify and understand the connections and associations between properties, forces, objects, people and ideas, including the human community's connection with the worlds in which we live. Any change in relationship brings consequences—some of which may occur on a small scale, while others may be far reaching, affecting large systems like human societies and the planet as a whole
System	Systems are sets of interacting or interdependent components. Everything in the known universe is a component of a system and generally also a part of multiple interacting and interdependent systems. Systems provide structure and order in both natural and human environments. Dynamic and complex in nature, systems rely on a state of equilibrium and are very vulnerable to change.

Source: International Baccalaureate Organization, 2015b, p. 55.

Table 3: Related Science concepts

Balance	The dynamic equilibrium that exists among members of a stable natural community
Environment	All of the biotic and abiotic factors that act on an organism, population or community and influence its survival, evolution and development
Transformation	A change from one well-defined state to another well-defined state; an alteration in form or condition, including energy, particle nature, cell and organism
Consequences	The observable or quantifiable effects, results, or outcomes correlated with an earlier event or events.
Form	The features of an object that can be observed, identified, described, classified and categorized.
Models	Representations used for testing scientific theories or proposals that can be accurately repeated and validated; simulations used for explaining or predicting processes which may not be observable or to understand the dynamics of multiple underlying phenomena or a complex system.
Function	A purpose, a role or a way of behaving that can be investigated; a mathematical relationship between variables.
Movement	The act, process, or result of displacing from one location or position to another within a defined frame of reference.
Patterns	The distribution of variables in time or space; sequences of events or features.
Evidence	Support for a proposition derived from observation and interpretation of data.
Interaction	The effect or effects two or more systems, bodies, substances or organisms have on one another, so that the overall result is not simply the sum of the separate effects.
Energy	The capacity of an object to do work or transfer heat.

Source: International Baccalaureate Organization, 2015b, p. 55.

The MYPIB curriculum design enables students to view the same concepts from a variety of perspectives, and is instrumental in producing a global thinking and international mindset as envisioned by the International Baccalaureate programme.

Other ways of connecting the big ideas of STEM can be explored, based on the context of each country.

2.2.3 Technical Knowledge associated with STEM careers

Besides providing basic education for students, secondary schools also prepare students for future careers. Curriculum developers need to provide students with technical knowledge, which is associated to STEM careers (Carnevale et al., 2011; Siekmann and Korbel, 2016). In the era of the 4th IR, technical knowledge is a specific form of knowledge responding to the needs of specific careers or industries. Technical knowledge encompasses vocational knowledge and required knowledge for all levels of engineers as well as technicians. Examples are provided in Table 4 (below).

Table 4: Examples of Technical Knowledge associated with specific career domains

Technical knowledge	Elaboration
Engineering and Technology	Knowledge of the practical application of engineering science and technology. This includes applying principles, techniques, procedures, and equipment to the design and production of various goods and services.
Computers, Electronics and Programming	Knowledge of circuit boards, processors, chips, electronic equipment, and computer hardware and software, including applications and programming.
Design and Technology	Knowledge of design techniques, tools, and principles involved in production of precision technical plans, blueprints, drawings, and models.
Production and Processing	Knowledge of raw materials, production processes, quality control, costs, and other techniques for maximizing the effective manufacture and distribution of goods.
Building and Construction	Knowledge of materials, methods, and the tools involved in the construction or repair of houses, buildings, or other structures such as highways and roads.
Mechanical	Knowledge of machines and tools, including their designs, uses, repair, and maintenance.
Mathematics	Knowledge of arithmetic, algebra, geometry, calculus, statistics, and their applications.
Physics	Knowledge and prediction of physical principles, laws, their interrelationships, and applications to understanding fluid, material, and atmospheric dynamics, and mechanical, electrical, atomic and sub-atomic structures and processes.

Technical knowledge	Elaboration
Chemistry	Knowledge of the chemical composition, structure, and properties of substances and of the chemical processes and transformations that they undergo. This includes uses of chemicals and their interactions, danger signs, production techniques, and disposal methods.
Biology	Knowledge of plant and animal organisms and their tissues, cells, functions, interdependencies, and interactions with each other and the environment.
Operation, Operations Monitoring and Control, troubleshooting	Controlling operations of equipment or systems, watching gauges, dials, or other indicators to make sure a machine is working properly, determining causes of operating errors and deciding what to do about it.
Equipment Maintenance and Repairing	Performing routine maintenance on equipment and determining when and what kind of maintenance is needed, repairing machines or systems using the needed tools.
Systems Analysis and Evaluation, Quality Control Analysis	Determining how a system should work and how changes in conditions, and the environment will affect outcomes, identifying measures or indicators of system performance and the actions needed to improve or correct performance, relative to the goals of the system.

Source: Carnevale et al., 2011; Siekmann and Korbel, 2016.

2.3 STEM Skills

Skills required in carrying out STEM-related tasks include cognitive, manipulative, technological skills and collaboration and communication skills. However, as Industrial 4.0 advances, both STEM and non-STEM tasks are in dire need of young people who have developed/are developing and can apply the broad skill-set. In light of the rapid rate of progress in the STEM fields, all learners need to be engaged in continuing professional development or continuous enhancement of such competencies.

- *Cognitive skills*

Cognition refers to the mental process of understanding through thinking and experiences. The range of cognitive skills needed include: information management and processing, (identifying, collecting, processing and using relevant data to make decisions) critical, creative and analytical thinking, problem solving skills, scientific investigation, creativity and computational thinking. These skills are not mutually exclusive.

The hallmark of STEM is its uncompromising reliance on scientific methodology and evidence to assess the validity of any argument, idea or finding. Any conclusion or decision made within the STEM fields must be a result of rigorous reasoning and logical deduction, through critical and analytical thinking. Critical thinking consists of objectively evaluating and analysing an issue in order to form a judgment. Analytical skills enable one to systematically visualize, articulate and conceptualize a problem as well as a solution, involving the following:

> *'The act of arguing is using evidence to support a claim. In the STEM fields, this means using analytical and critical-thinking skills to look for patterns in data, trying to determine what those patterns mean, and then using that data to support a claim' (Adams, 2017).*

Analytical thinking requires knowledge of numeracy, mathematical principles, scientific principles and methods, as well as an understanding of empirical data and methods to deal with it. It requires the use of mathematical processes involving concepts such as representation, reasoning, communication, problem solving and making connections (National Council of Teachers of Mathematics, NCTM 2000).

These skills trigger and support mathematical thinking and reasoning like mathematicians, who use numerals (both figure and symbol) for systematic and critical assessment of complex problems and mathematical processes in identifying and exploring patterns in order to reason and find solutions to identified problems.

- *Information Processing - Data Interpretation and Data Analysis*

As we advance further into the 21st century, increasingly large amounts of information and 'big data' are being gathered and used in all walks of life. Information processing skills are thus required to find, collate, organise and select valid information for specific tasks in order to generate, understand, interpret, analyse, and extrapolate empirical data, test its authenticity, validity and reliability and display findings in effective ways:

> '*Students need to be able to make a decision not just based on what they think or feel, but on scientific data that supports the best solution. Everyone needs to know how to do this. It doesn't matter whether you go on to a career in STEM or not—you need to know how to use data to make informed decisions in your life' (Stacy Klein-Gardner, as cited in Adams, 2017).*

- *Problem Solving and Engineering Thinking*

The process of problem solving consists of identifying and breaking down complex problems into parts or components, analysing data, developing solutions, evaluating options and implementing solutions. Problem solving is a feature of STEM studies and STEM careers, as is explained by a STEM practitioner:

'I didn't use the calculus I learned to solve problems on paper, but the way it taught me to solve problems and to think about problems was really important' (James Brown, as cited in Adams, 2017).

Engineers use problem solving skills routinely, since their jobs entail devising models or systems to understand problems, design solutions, test solutions, find alternative solutions, and inform decision-making processes. Generally, engineering is referred to as branch of STEM which designs, builds and uses machines. In the process of creating solutions or products, engineers also need to consider factors such as safety and sustainability, as well as the needs of their clients. Thus, problem-solving skills are part of engineering mind-sets or engineering thinking, which describes the ways engineers think and act, involving systems thinking, problem-finding, adapting, creative problem solving, visualising and improving (Royal Academy of Engineering, 2014; Institution of Mechanical Engineers, 2016).

Although the discipline of engineering encompasses a broad range of more specialised fields, such as mechanical engineering and civil engineering, each of them uses engineering thinking in a similar way to ensure efficient and safe operations. STEM technology-related careers also include, for example, food scientists, surveyors and musical technologists.

- *Scientific Investigation*

Scientific investigation is a systematic methodology that scientists use to explore and find answers to existing phenomena in the world around them. It involves conducting scientific investigation, including science process skills and manipulative skills to observe phenomena, formulate hypotheses, investigate, experiment and test hypothesis, analyse data and develop conclusions that confirm, reject or modify a hypothesis.

Science process skills are skills that are required in the process of finding solutions to a problem or making decisions in a systematic manner (Padilla, 1990). They involves mental processes that promote critical, creative, analytical and systematic thinking. Science process skills translate to observing, classifying, measuring, making inferences, predicting, communicating, using space-time relationships, interpreting data, defining operationally, controlling variables, making hypotheses, and experimenting (Bahagian Pembangunan Kurikulum, 2016a, 2016d).

Mastery of science process skills, together with knowledge and appropriate scientific attitudes, are essential for learning in science education. PISA and TIMSS, two internationally acclaimed school-based assessments, use scientific investigation and experimental skills within their respective assessment frameworks, challenging students to interpret data and evidence scientifically, make hypothesises and control variables (Martin and Mullis, 2013; OECD, 2017).

- *Computational Thinking and ICT*

The effective use of Information and Communications Technology (ICT) skills and connectivity are important to the advancement of the STEM fields as the 4th IR progresses. Basic ICT skills include the technical ability to use a computer, tablet or mobile phone, send emails, browse the internet, make a video call and use computer software (such as Word, PowerPoint, Excel) to search for information and create presentations (Bahagian Pembangunan Kurikulum, 2016c). Computational thinking involves formulating problems and representing solutions in ways that can be effectively carried out by an information-processing agent, which could be a human, a machine or both (Wing, 2006, 2008; Bahagian Pembangunan Kurikulum, 2016c). Coding involves programming sets of instructions or algorithms to enable computers or ICT gadgets to perform certain tasks. The skills involved in computational thinking include logical reasoning, decomposing, pattern recognition, abstraction, and algorithm design (Wing, 2006, 2008; Bahagian Pembangunan Kurikulum, 2016c).

- *Design Thinking, Creativity and Innovation*

The 4th IR is making us even more dependent on engineering and technological innovation as a result of which design thinking has become a necessity in this age of great innovation, invention, creativity and design.

Design thinking provides a structured framework that encourages and fosters a learner's creativity and innovation. It involves a structured framework of creative strategies and processes to develop products and solutions but eschews the idea of a sequence of orderly steps or rigid techniques or rules. Rather it is about making creative ideas viable and putting ideas to work, guided by an individual's inspiration, empathy and ideation. Design thinking integrates critical and creative thinking using phases of information gathering, creative brainstorming, ideation, prototyping, trial and error, review, redesign, refinement, testing and implementation that can be effectively applied to STEM learning and STEM careers.

Creativity is the ability to use imagination to create something. A creative person can perceive the world in different and sometimes entirely new and novel ways by finding hidden patterns and making connections between seemingly unrelated phenomena.

Innovation, on the other hand, is related to something more tangible and involves making changes and improvements to existing products, processes and systems. Creativity and innovation can be fostered in various ways:

> *'Creativity can be simple and complex at the same time. We don't always teach to think outside of the box. You've got to look at a problem from a different perspective sometimes. Teachers can nurture this by asking open-ended questions. In mathematics and science, you can show different models so students get varying ideas of how it might*

look to bring together one idea. Or don't show a model at all and leave it a little open-ended so they have to come up with a solution on their own. Ask: 'Why do you think this is?' Reflecting and explaining what they did to solve a problem can foster creativity and teach collaboration—another important skill' (Jenny Nash, as cited in Adams, 2017).

- *Manipulative and Technological Skills*

Manipulative skills refer to the psychomotor skills involved in correctly and safely using and handling scientific and/or technical equipment, apparatus, specimens and substances which may be specific to a particular career or vocation (Siekmann and Korbel, 2016) such as electricians, cardiovascular technologists, aircraft mechanics, auto technicians, and mechatronics engineers.

Technological change can be fast and the needs of the society or country can change at any moment (Siekmann and Korbel, 2016) so vocational and technological skills' training has to be predictive of and responsive to the dynamics of the labour market. Vocational and technical education institutions have to decide on which types of skills to focus on, and which modes of training to provide (often including apprenticeship). A major concern is the proportion of vocational training that can be effectively offered within formal education settings. Some countries provide vocational/technological skills' training at secondary schools which assist students to make more informed decisions about their future careers. However, because vocational skill-sets constantly and rapidly change, schools often find it a challenge to keep up to date with innovations.

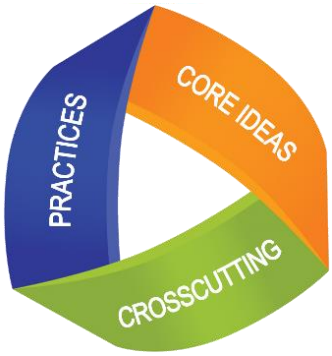
- *Collaboration and Communication Skills*

Effectively collaborative and communication skills do not always occur naturally and need to be explicitly developed, as most tasks are complex and interrelated, and cannot be achieved by a single person's effort but, rather, through effective teamwork. Effective collaboration gives each team member an equal chance to participate and communicate ideas within the space of a shared responsibility. Establishing common goals gives team members meaningful reasons to work together and to share responsibility to achieve shared goals and impact. Being able to work independently and in teams and to convey information to other team members or stakeholders in clear and effective ways are fundamental skills for all.

2.4 STEM Attitudes and Values

The US National Research Council have employed the term 'STEM practices' to describe the attitudes/behaviours/activities that STEM workers use as they investigate phenomena and design, build models and systems to solve problems. The NGSS model of 'Three Dimensional Learning' (see figure 2) illustrates STEM as a body of knowledge with core and cross-cutting ideas and STEM practices which combine to form each learning standard.

Figure 2 : Three Dimensional Learning



Source: NGSS Lead States, 2013a.

The term practice implies that engaging in scientific investigation or problem solving requires not only skills but also specific cognitive and social knowledge values and attitudes The NGSS stipulate that students who engage with STEM practices should have internalized a STEM philosophy and are likely to apply these practices continuously in their everyday lives and in their future careers. Engaging in STEM practices gradually consolidates and strengthens an individual's STEM competence, incorporating STEM knowledge, skills attitudes and values which combine and lead to competences that enable a better understanding of STEM-related jobs such as engineering and research science.

Table 5: STEM Practices

	Practice	Elaboration
1	Asking questions and defining problems	- Students ask questions and explanations of how the natural and designed world works and which can be empirically tested. - Students ask questions to clarify problems to determine criteria for successful solutions and identify constraints to solve problems and to clarify ideas.
2	Developing and using models	- Students develop and use models in the form of replicas, diagrams, mathematical representations (graph, formula), analogies, and simulations.
3	Planning and carrying out investigation	- Students plan and conduct investigations through inquiry.
4	Analyzing and interpreting data	- Students collect, analyse, interpret and present data so that the audience can understand and apply what they have learned.

	Practice	Elaboration
5	Using mathematics and computational thinking	- Students use mathematics (logic, geometry and calculus) to represent physical variables and establish relationships in making quantitative predictions. - Students use computational thinking to design strategies to find and organize data, design algorithms, use and form simulations and develop systems.
6	Constructing explanations (for science) and designing solutions (for engineering)	- Students reflect their understandings through the use of words, graphics or formula, verbally or written. - Students systematically design to find a solution to problems based on scientific knowledge and models of the material world, balancing the competing criteria of desired functions, technical feasibility, cost, safety, aesthetics, and compliance with legal requirements as well as how well the proposed solutions meet criteria and constraints.
7	Engaging in argument from evidence	- Students argued and reasoned based on evidence to identify the best explanation for a natural phenomenon or the best solution to a design problem. - Students use argumentation to listen to, compare, and evaluate competing ideas and methods based on evidence.
8	Obtaining, evaluating, and communicating information	- Students search, evaluate, communicate clearly and persuasively the ideas and methods they generate using multiple ways such as diagrams, graphs, equations and writing. - Students critique and communicate ideas individually and in groups through extended discussions.

Source: NGSS Lead States, 2012, 2013a.

The attitudes and moral values outlined below amplify the STEM practice of scientific inquiry and contribute to a STEM way of investigation, objective thinking and rational action based on systematic and precise procedural processes, informed by values of curiosity, integrity, objectivity, open-mindedness, diligence and perseverance in search of truth, as outlined in table 6 (over).

Table 6: STEM Values and Ethics and its Related Activities

STEM values and ethics	Related activities
Curiosity	- Interest towards the environment - Self-directed initiation for exploration and searching of information and materials - Doing own research
Integrity	- Acts with integrity - Honesty in reporting observation and experimental findings - Accurate in recording and validating data
Objectivity	- Record data as observed, not affected by feelings, imagination - Explain observations rationally
Open-minded	- Accept others opinion - Changing one's stand only based on evidence - Not prejudice - Flexible
Diligent and perseverance	- Ready to repeat the experiment - Determination in carrying out a task - Ready to accept critics and challenges. - Persevere to overcome problems and challenges
Systematic	- Carry out activity in a systematic and orderly manner and abide to suitable time.
Cooperative	- - Work together in carrying out activities and experiments.
Responsible	- Being responsible about the safety of oneself, others and the environment - Understands and weighs up consequences of action
Precision	- Conduct experiment to collect accurate data - Respect precision in measurement
Appropriate Risk Taking	- Be willing to try different ways of collect data - Be willing to explore new areas in STEM
Ethical decision-making	- Evaluating and choosing among alternatives in a manner consistent with ethical principles
Appreciate the contribution of STEM to our everyday living	- Use STEM inventions responsibly - Uphold strong STEM ethics

Source: Adapted from Bahagian Pembangunan Kurikulum, 2016d; Chowning and Fraser, 2007.

The domain of ethics provides 'a systematic, rational way to work through dilemmas and to determine the best course of action in the face of conflicting choices' (Chowning and Fraser, 2007, p. 27). The key to making effective, ethically-informed decisions is to think about choices in terms of their ability to accomplish important goals. This requires an understanding of the difference between immediate and short-term goals and longer-range goals. The "Character-Based Decision-Making Model", developed by the Josephson Institute of Ethics, can be helpful as a guide when facing ethical dilemmas. It involves taking into account and reflecting upon the

interests and well-being of all who may be affected by a decision in the short and longer-term. The underlying principle is that decisions should be based on providing for the common good and avoiding harm where possible.

Making ethical choices requires the ability to distinguish between competing options and weighing up the likely impact of different choices, involving a commitment to do the right thing: to collect and evaluate sufficient information; to identify who may be affected by a decision and how it is likely to affect them; to foresee potential consequences and risks or unintended results; and to consider alternatives, so as to act morally and consistently. Some decisions involve competing ethical values, where the only viable option requires the sacrifice of one ethical value over another. In such cases, decisions need to consider the balance of good in the longer term and the least amount of harm to the greatest number of people over time.

STEM ethics thus depend on the development of adequate knowledge, skills, attitudes and values and a deep sense of responsibility as citizens. Engaging with authentic real-world scenarios, problems and dilemmas that require interventions and innovative solutions, such as dealing with food or housing shortages, climate change, migration, genetic testing, etc., provide opportunities for students to learn how to frame and guide interventions and innovative solutions for the greatest good and least harm. Thus, ethical decision-making should is an integral part of good STEM learning and practice.

CHAPTER 3: APPROACHES TO STEM EDUCATION

3.1 Introduction

In the planning of STEM education at a school level, the basic question is often about the extent to which: the four disciplines of science, technology, engineering and mathematics should be integrated and taught as one STEM subject. This question is pertinent for the majority of school systems throughout the world. Debates on whether STEM should be considered as a meta-discipline (Vasquez, 2015) or a new whole (Lantz, 2009); and the ways in which STEM should be taught, as 'an integration of formerly separate subjects' or as 'a new and coherent field of study' (Vasquez, 2015) have generated confusion and uneasiness within the education sector.

Different models of STEM integration into curriculum and teaching practices exist. Dugger, (2010) argued that there are a number of ways that STEM can be taught in schools today. One way is to teach each of the four stem disciplines individually. Another is to teach each of the four STEM disciplines with more emphasis going to one or two of the four (which is what is happening in most U.S. schools today). A third way is to integrate one of the STEM disciplines into the other three. For example, engineering content can be integrated into science, technology, and mathematics courses. [And lastly] a more comprehensive way is to infuse all four disciplines into each other and teach them as an integrated subject matter (in Asunda, 2014 p 4-5).

In most education systems, schools have a daily timetable for classes of students in which learning is organised by subjects and by corresponding segments of time, and the subjects are taught according to this pre-determined timetable. In this case, the approach to STEM education is more discipline-specific. However, there are also schools adopting a partial interdisciplinary approach, where the boundaries between subjects are less obvious. These schools adopt the thematic approach where learning is organised by themes. The sections below elaborate on various approaches to STEM learning and can be adapted depending on the context.

3.2 STEM through a discipline-specific approach

A discipline-specific approach is adopted in the majority of schools, at secondary levels, with perhaps more integration evident at primary level. It tends to be common practice that all students learn the subject areas of science and mathematics. Technology and engineering related subjects such as Design and Technology, ICT, Computer Science and Electrical Engineering tend to be offered as electives, especially at secondary schools. STEM-related vocational courses are sometimes provided in secondary schools.

In this STEM discipline-specific approach teachers still teach their option subjects and STEM is more of an umbrella term or convenient abbreviation of the four disciplines, which remain distinct and separated. **IF** each discipline practices the philosophy of scientific, mathematical,

engineering, technological and design thinking, then each discipline on its own can provide a holistic STEM education to students, but the links between the disciplines may not be made explicit and the overall competences elaborated above may not be acquired. .

To encourage more students to study STEM at a tertiary level or embark into a STEM career, individual STEM subjects are sometimes packaged together to provide indicators to students on subjects best-fit for them to take in preparation of their involvement in STEM learning and careers (IBE-UNESCO, 2017).

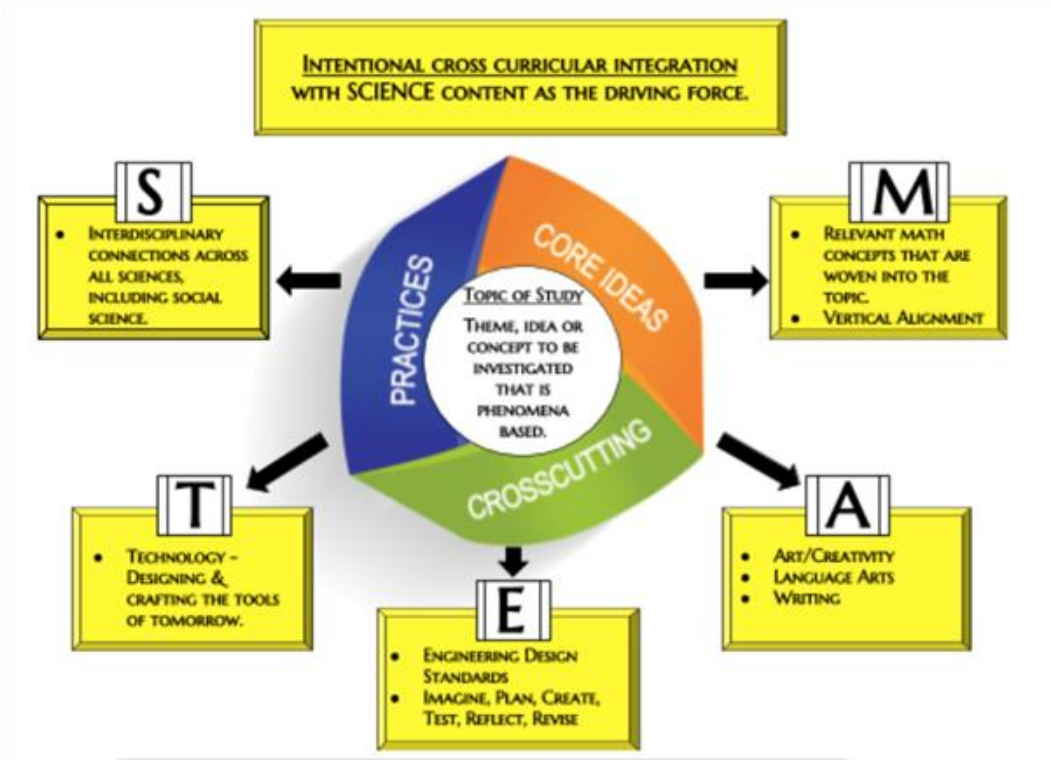
3.3 STEM through integrated approaches

Interdisciplinary or integrated STEM education is a fusion of the four disciplines of Science, Technology, Mathematics and Engineering, where the focus of learning is not the individual discipline in itself, but on solving real-world problems. The changing demand for competence in the era of Industrial Revolution 4.0, which continuously alters the global labour landscape, is driving the need to consider multifaceted, trans-disciplinary and integrated competences (Marope, 2017). STEM competence based on an interdisciplinary approach guides students to think outside the box to identify problems and build or construct solutions.

Research suggests that an interdisciplinary or integrated curriculum provides opportunities for more relevant, less fragmented, and more stimulating experiences for learners, including improving student motivation to learn; enhancing attitudes and interest in school; making students better problem solvers, innovators, inventors, self-reliant, logical thinkers, and technologically literate (in Stohlmann et.al., 2012). Similar benefits are claimed in relation to integrated approaches to STEM education, which aims to combine science, technology, engineering, and mathematics in different ways based on connections between the subjects and real world problems.

- A **multidisciplinary** approach uses a **theme** that appears in each STEM and core course during the same time period to draw connections among subjects. The subjects, however, may be taught separately and the connections are made through teacher and student reflection. The following example from Romoland School District in the United States seeks to integrate the Arts and Social Sciences to broaden STEM integration into STE**A**M.

Fig 3: An example of STE**A**M integration (including the Arts & Social Sciences with STEM)



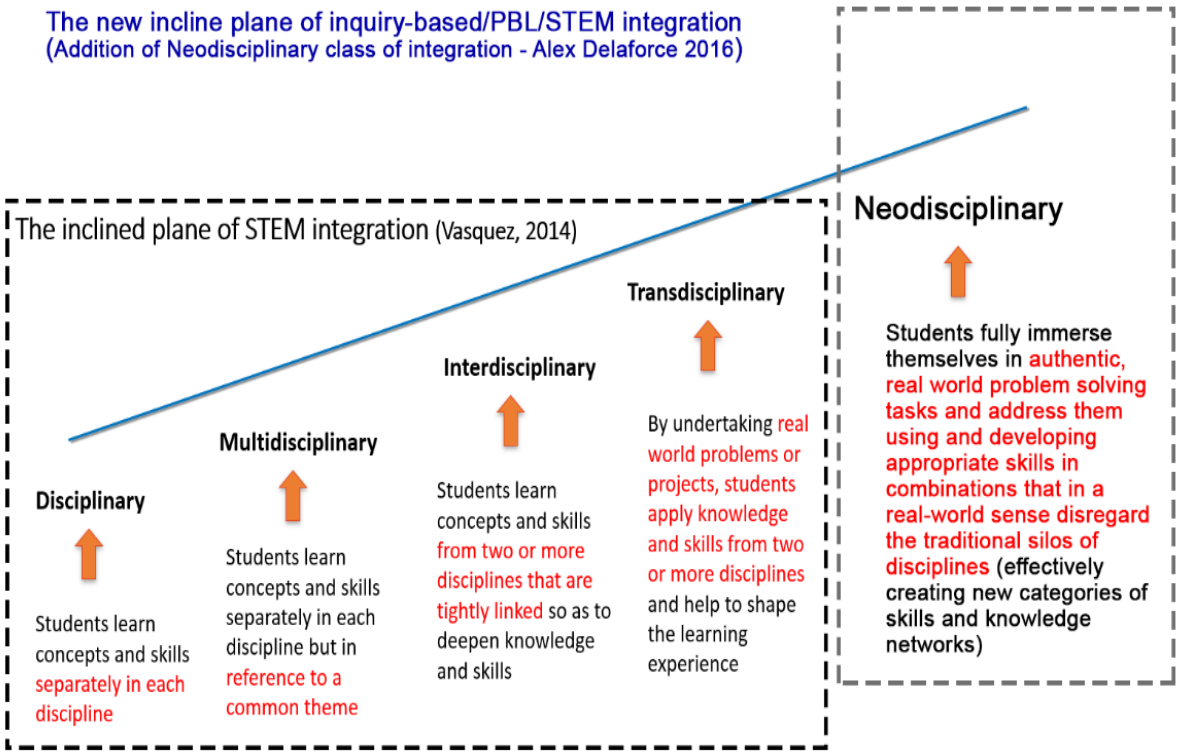
Source: Romoland School District USA https://www.romoland.net/Page/1536

- An **interdisciplinary** approach achieves a higher level of integration across subjects, for example, by focusing on a **shared concept,** such as "cause and effect" (as in the examples from the International Baccalaureate). In an effective interdisciplinary approach, relevant disciplines come together to **blur** and overcome any separation of skills and knowledge within the disciplines.

- A **transdisciplinary approach** goes further than interdisciplinary, by seeking to fully **dissolve the boundaries** between the conventional disciplines and organizes teaching and learning around the construction of meaning **in the context of real-world problems or themes**.

- A **neo-disciplinary approach** (Delatorre 2016) proposes a new 'neo-disciplinary' categorisation that disregards traditional subject boundaries altogether 'to create new categories of skills and knowledge networks'.

Fig 4: The inclined plane of STEM integration (Vasquez 2014) extended (Delaforce, 2016)

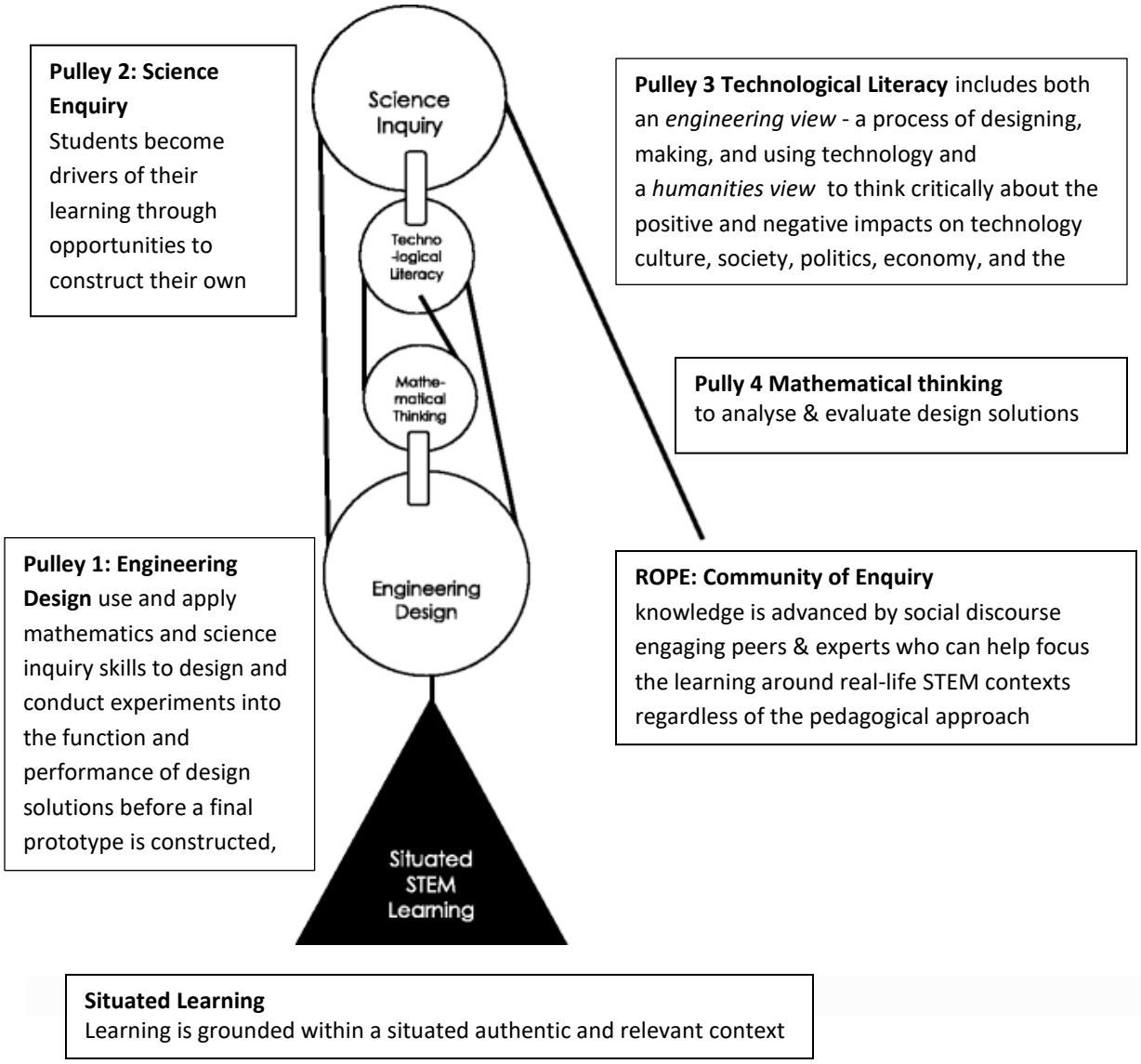


Source: Delaforce 2016 http://delaforce.info/wp-content/uploads/2016/10/Neodisciplinary-1.png

The following graphic illustrates a conceptual framework – designed as a block and tackle of four pulleys - for integrating the diverse aspects of STEM learning.

> 'The illustration connects situated learning, engineering design, scientific inquiry, technological literacy, and mathematical thinking as an integrated system.
>
> Each pulley in the system connects common practices within the four STEM disciplines and are bound by the rope of community of practice. The pulley system must work in harmony to ensure the integrity of the entire system' (Kelly and Knowles (2016) p. 4).

Fig 5: Graphic of conceptual framework for STEM learning



Source: Adapted from Kelley, T R. and Knowles J.G (2016) P4.

3.4 STEM through pedagogical approaches

A range of inquiry-based/ problem-solving pedagogical approaches can be used to integrate STEM into the curriculum. These might be regarded as 'in-between' approaches between discipline-based learning and multi-disciplinary/transdisciplinary approaches, for example:

- Focusing **on real world authentic problems** in real-world contexts. offering students opportunities to make connections across disciplines and to develop problem solving, diagnostic and critical thinking skills, including research, hypothesis testing, analysis, synthesis and strong deductive reasoning to realise solutions to real problems

- Placing a **design activity** at the beginning or at the end of an assignment so that students are challenged to apply acquired STEM knowledge to complete an assignment because purposeful design and inquiry' (PD&I) combines technological design with scientific inquiry in the context of technological problem solving (Sanders (2009) in Asunda, (2014) p5-7)).

- **Problem-based learning (PBL**) conducting research and applying knowledge and skills to develop a viable solution to a defined problem. Critical to the success of PBL is the selection of ill-structured problems (often interdisciplinary) and the availability of support to guide the learning process and to debrief at the end of the learning experience. While the instructor supports the process s/he does not provide information related to the problem, but expects the learners to make their thinking clear (Savery, 2006, in ibid.).

- **Project or Inquiry-based learning** -similar to problem-based learning, in that the learning activities are organized around achieving a shared goal, but the role of the instructor, as both a facilitator of learning and a provider of information, is stronger, whereas the learner's role in setting the goals and parameters for the investigation is less defined (ibid).

If handled well by skilled teachers these contextually situated, activity based approaches help students to make personal meaning of their learning experiences, increasing the probability that what is learned will be retained and can be transferred for later use.

It is interesting to note that at the tertiary education level, many universities teach interdisciplinary courses to engage students with a more realistic picture of society and industries' current needs. The expected outcomes of a STEM interdisciplinary approach are that:

> *'A person with interdisciplinary STEM competency might be expected to explain and analyse climate change, because they are familiar with the principles of science and mathematics; … to design tools for analysis and to engineer measurement technology and understand the use of other machinery and software in this area. This suite of knowledge would be complemented by an understanding of how this phenomenon affects society, and the person would understand how to collaborate with others to remedy adverse effects. In reality however the application of STEM skills and knowledge for designing and building solutions will be achieved through the collaboration of many people and teams'* (Siekmann and Korbel, 2016, p. 19).

Within schools, interdisciplinary and transdisciplinary approaches to STEM learning remain the exception rather than the rule, but could be a potential solution for the education sector to make learning more contextually meaningful for students in the future. Notable ongoing programmes that advocate Interdisciplinary and transdisciplinary approaches, include:

- *The International Baccalaureate (IB)* which advocates pedagogical approaches focusing on sustained inquiry. In its *Middle Years Programme (MYPIB*) teachers and students develop statements of inquiry and inquiry questions as they explore their area of study within and across disciplines. Through inquiry-based learning, students develop a conceptual understanding of the big ideas in STEM within global contexts, as well as skills in thinking, communication, self-management and research (International Baccalaureate Organization, 2015b, 2015c).
- *La main à la pâte* **-** meaning collaborative, hands-on way of working – was founded in 1996 by and is implemented throughout France and internationally, in more than 35 countries worldwide. It proposes STEM teaching and learning methods aimed at engaging and encouraging students and to explore, design and conduct investigations into issues related to their everyday life, draw conclusions on their own and communicate their findings(La main à la pâte, (2007); SEAMEO RECSAM and French Academy of Science, (2007)).

A major challenge in progressing integrated approaches in schools is the readiness of teachers who have gone through specific disciplinary training in teaching colleges and universities. It is challenging for STEM teachers to master all STEM knowledge. To produce teachers who are able to teach STEM in an integrated manner, their training needs to focus on interdisciplinary themes and pedagogical approaches that encompass a broader spectrum of content, methodologies and practices. This cannot be achieved overnight. It requires a long-term perspective and planning. Another challenge is to teach the necessary STEM knowledge within the amount of time allocated in school timetables. There is also a need to keep STEM knowledge relevant, so that it does not become outdated.

In a year-long partnership with a middle school researchers developed a 'support, teaching, efficacy, and materials' (s.t.e.m.) model of for teaching integrated STEM education The model identified and summarised the key support factors that are considered essential to supporting teachers in implementing an integrated approach to STEM (see Table 7 over).

The necessity for high levels of support to develop the knowledge, skills, materials and expertise in to teach an integrated approach to STEM subjects deters curriculum developers across countries from fully adopting an interdisciplinary approach.

Table7: The support, teaching, efficacy, and materials (s.t.e.m.) model for teaching integrated STEM education

Support	
• Partner with a university or nearby school • Attend professional development • Teacher collaborative time	
Teaching	Classroom Practices
• Focus on connections • Understand student misconceptions • Understand student capabilities • Problem-solving based • Student-centred • Build on previous knowledge • Focus on big ideas, concepts or themes • Integrate technology • Real world and cultural relevance	• Posing questions and making conjectures • Justifying thinking • Writing for reflection • Focus on pattern understanding • Use assessment as part of instruction • Co-operative learning • Effective use of manipulatives • Inquiry
Efficacy	
• Content knowledge and pedagogical knowledge contribute to self-efficacy • Commitment to STEM education is vital • Planning and organisation are critical	
Materials	
• Technology resources • Broad view of technology • Material kits for activities • Room space and storage • Tables for group work	

Source: Stohlmann, Moore and Roehrig (2012)

Engaging external professionals or experts can make STEM teaching and learning more contextual, meaningful and impactful. For example, schools can employ scientists, engineers and digital specialists to: coach students; co-teach with teachers; involve students in their ongoing research and innovations; and guide them to design experiments and create their own innovations. This can bridge or overcome teachers' lack of readiness or apprehension about adopting an interdisciplinary approach to STEM, while preserving the individual disciplines intact to serve the specific technical requirements of higher education, industry and specialisms within the STEM field.

CHAPTER 4: INTEGRATING STEM INTO CURRICULUM FRAMEWORKS

4.1 Integrating STEM philosophy into National Curriculum Frameworks

Educational policy, educational programmes and curriculum need to be futuristic in the sense to preparing future workers, leaders and citizens of a country. As we move towards the types of society we envision, it is important to create awareness around STEM and develop STEM competence through education, reaching out to all learners, including disadvantaged and marginalized ones. STEM related educational programmes or curriculum aim to fulfil the needs of different strata of society as well as the needs of the various professional levels in the STEM industries.

As STEM education responds to societal needs, values and concerns, it is important to develop a rounded understanding of STEM philosophy and practice. The focus should not only be on utilitarian aspects of STEM, but also on valuing and appreciating the contribution that the disciplinary areas of science, mathematics, engineering and technology can bring to STEM thinking and action. The evidence-based approach of STEM, with its systematic exploration, and inquiry modes of learning and problem-solving, have many underpinning philosophical values, which need to be considered when incorporating the philosophy of STEM into the national curriculum framework.

Many countries, especially developing countries, have elaborated their national curriculum policy to spearhead the development of their country's human resources and economy as well as its physical development. In these policies, STEM Education is an important component. For example:

- In Malaysia, the National Philosophy of Science and Technology (S&T) Education stipulates that Science and Technology (S&T) education promotes a culture that encourages the development of competitive, dynamic, resilient and efficient individuals who master S&T competence and knowledge (Bahagian Pembangunan Kurikulum, 2016d). Guided by this philosophy, the Malaysian MoE has developed various core STEM subjects, as well as vocational and technical subjects within the primary and secondary school curriculum (Bahagian Pembangunan Kurikulum, 2016a). Although not all students will become STEM professionals in the future, it is important that they acquire sufficient STEM competence to attain and pursue other future careers. Whether they work in STEM or non-STEM areas, they will be using some forms of STEM competence (e.g. digital competence).

- In Cambodia, the National Policy on STEM Education (inaugurated in 2016) marked the country's commitment to use STEM as an enabler to develop highly qualified and responsible human resources, to achieve the sustainable and inclusive development of Cambodia in accordance with Cambodia's Industrial Development Policy. The policy lays out the

mechanisms for developing a legal framework and capacities, obtaining financial support, and monitoring STEM Education to achieve its target on STEM human capital (Ministry of Education, Youth and Sport Cambodia, 2016)

4.2 Identifying STEM concepts and ideas within national curricula

A great concern for curriculum developers and teachers is to decide which basic (STEM) elements to teach at primary and secondary school levels, in order to prepare students for further learning in STEM areas (in higher education or in the workplace). Information overload at the early stages of education can be detrimental to learning, motivation and engagement. A balance needs to be struck between teaching 'the basics' and keeping pace with the latest STEM ideas and challenges. As countries attempt to integrate the four major disciplines of STEM into their curricula, they need to identify cross-cutting concepts and ideas across the four disciplines which can frame their approach to STEM and which can act as lenses through which students can view and make sense of the world around them (Harlen 2010, 2015). The examples provided in Chapter 4 by the NGSS Lead States in the United States, and the International Baccalaureate, are good starting points.

4.3 Aligning competence across STEM and NON- STEM Disciplines

School education remains primarily organised into subjects, which are either STEM related (e.g. Science, Mathematics, etc.) or non-STEM related (e.g. The Arts, Humanities and Languages). In the search for commonalities and focal points across all subjects, a range of common skills, attitudes and values are identifiable that play out in slightly different ways within each subject, that can lead to generic skills, values and attitudes being developed within and across both STEM and non-STEM subjects.

Identifying and aligning these skills, values and attitudes to big ideas within and across disciplines can facilitate the development of a contextual and meaningful competency-based curriculum. This exercise will also prompt curriculum developers and educators and to expand to be more inclusive of STEM and Non-STEM disciplines; paving the way to a more meaningful, holistic and competency-based experience for students. The following unpublished example from Malaysia's Curriculum Development Division may prove helpful.

Table 8: Mapping Skills in STEM and non-STEM Disciplines

		Subjects							
		SCIENCE	TECHNOLOGY	ENGINEERING	MATHS	HUMANITIES	LANGUAGES	ARTS	PHYSICAL ED
A). Skills in obtaining and collecting information									
Listening and Questioning	Paying close attention, sensitive to needs/situation and questioning back.	[1]							
Observing	Observe systematically, accurately and sensitively.								
Seeking and finding resources	Finding resources and information from computer, library, people etc.								
Investigating and exploring	Identifying problem, making inquiry, designing investigation/ exploration, conducting research and developing questions which are focused, critical and creative.								
Collecting data	Planning, sequencing, classifying and recording data.								
Solving problem and making conclusion/decision	Identifying problem, investigating background, design method of solving problem, making conclusion.								
B). Skills in organising and displaying data systematically									
Recording	Recording data into tables, charts accurately, and systematically.								
Compare and contrast	Identify similarities and differences and determine criteria which differentiate them.								
Categorising and classifying	Identifying common feature/ characteristic to facilitate classification.								

[1] Example of how each competency can be developed within each of these subjects should be stated in this space of the table.

Planning and managing data	Organising a filing system, creating a system to facilitate managing of data.								
	Planning to design investigation.								
Evaluating and reflecting	Reflect and identify new and important matter.								
	Identify the criteria (good and bad) and finding alternatives.								
Analysing	Investigate implication and relationship between related matters, identify cause and effect and new problem.								
C). Skills in conducting activities and handling materials and equipment (manipulative skills)									
Using equipment	Knowing how to use equipment correctly according to the requirement of the task, knowing how the equipment function, understand the limit of the equipment.								
Maintenance of equipment	Knowing how to keep equipment and keep stock, how to set up equipment, safety measure.								
Experimenting	Plan and conduct investigation/experimentation onto a hypothesis, collect data, analyse data and making conclusion.								
Develop and design	Develop and design a prototype for a certain objective.								
Calibrating	Calibrate equipment such as thermometer, weighing machines etc.								

Source: Curriculum Development Division, 2015, unpublished document.

A lifelong learning approach should be adopted when elaborating a national curriculum. STEM competence can be developed from the onset of early childhood education, through primary school, secondary school to post-secondary school as well as through on-the-job training in STEM and non-STEM subjects. The cradle-to-career programs spearheaded by the New York Academy of Science exemplify a lifelong learning approach to STEM. Through these programs, partnerships between education institutions and civil societies, business sectors, industries as well as

communities were developed and attention was given to the progression of students' learning from early childhood until adulthood (McLester, 2011).

4.4 Assessment of STEM Competence

Assessment involves the measurement and evaluation of learners' progress and achievements. It generally involves:

- Defining the objective of each assessment.
- Determining the criteria and rubric of the assessment.
- Designing the assessment tools/instruments to gather the required information.
- Conducting the assessment task(s) and/or relevant observations of student performance.
- Assessing the outcomes and related data according to the criteria and rubric set.
- Analysing the information obtained and making judgments about student achievement
- Identifying and communicating next steps in learning.

In many countries, mid-year and final-year school examinations, as well as public examinations at the end of certain levels of education, focus primarily on the assessment of STEM knowledge and do not effectively reflect the more holistic requirements involved in STEM competence and preparedness for the 4th IR. Examinations, however, are just one form of assessment. Best practice suggests that in assessment should include both formative and summative approaches. Activities such as carrying out a STEM project or an experiment, presenting its findings, as well as teachers' observations of group dynamics and individual participation in small group projects, can provide substantial information and content on the progress of students' learning in STEM. Thus, examination outcomes should be supported by evidence of engagement with inquiry projects and activities, to allow students to demonstrate their competence in practice. The criteria and rubrics for STEM assessment need to include consideration of the three main dimensions of STEM competence: knowledge, skills, values and ethics (including attitudes and actions). Table 9 provides a glimpse of the Middle Year International Baccalaureate (MYPIB) assessment criteria which focus is on understanding, communication and investigation in STEM. Table 10 and 11 list the assessment criteria for TIMSS and for PISA. All of these criteria are relevant and helpful for assessing STEM competence. It is necessary for curriculum developers to consider these assessment criteria as they develop STEM curricula.

Table 9: MYPIB Assessment Criteria

	A	B	C	D
Science	Knowing and Understanding	Inquiring and Designing	Processing and Evaluating	Reflecting on the impacts of science
Mathematics	Knowing and Understanding	Investigating patterns	Communicating	Applying mathematics in real-world contexts

Design	Inquiring and analysing	Developing ideas	Creating the solution	Evaluating

Source: International Baccalaureate Organization, 2014.

Table 10: Domains in TIMSS Science

TIMSS		Science	Mathematics
Content Domain		Biology, Chemistry, Physics, Earth Science	Number, geometric shapes and measures, data display, algebra, geometry, data and chances
Cognitive Domain	Knowing	Recall, recognize, provide examples	Recall, recognize, classify/order, compute, retrieve, measure
	Applying	Compare/contrast/classify, relate, use models, interpret information, explain	Determine, represent/model, implement
	Reasoning	Analyse, synthesis, formulate hypothesis/predict, design investigation, evaluate, draw conclusions, generalize, justify	Analyse, integrate/synthesize, evaluate, draw conclusions, generalize, justify
	Science Practice	• Asking questions based on observation • Generating evidence • Work with data • Making an argument from evidence • Answering research questions	

Source: Martin and Mullis, 2013.

Table 11: Aspects of the Scientific and Mathematical Literacy in PISA 2015

PISA	Scientific literacy	Mathematical literacy
Contexts	Personal, local/national and global issues, both current and historical, understanding of science and technology	Real world context: Personal, societal, occupational, scientific
Knowledge	• Content knowledge: natural world and technological artefacts • Procedural knowledge: how scientific ideas are produced • Epistemic knowledge: understanding of the underlying rationale for content knowledge and procedural knowledge	• Content: Quantity, uncertainty and data, change and relationships, space and shape • Processes: formulate, employ, interpret/evaluate • Mathematical thought and action
Competencies	The ability to: • Explain phenomena scientifically • Evaluate and design scientific enquiry	• Communication • Representation • Devising strategies • Mathematisation • Reasoning and argument,

PISA	Scientific literacy	Mathematical literacy
	• Interpret data and evidence scientifically	• Using symbolic • Formal and technical language • Operations • Using Mathematical tools

Source: OECD, 2017.

4.5 Challenges

Although the STEM acronym is in widespread use, yet an agreed definition and approach to STEM remains elusive in practice and policy, programme and practice challenges remain to be addressed at national/regional/state/district and school levels.

At policy level there needs to be a commitment to supporting all four disciplines in schools in an integrated way. This requires greater attention being paid to the place of engineering and technology alongside, or within, science and maths.

At national/regional/state/district teachers need to be trained to cope with the knowledge, epistemological and pedagogical principles of the contributory disciplines in order to be able embrace integrated approaches

At programme and examination levels there needs to be a commitment to defining and assessing programmes that address holistic global challenges, with adequate access to teacher resources to promote active investigation and creative design of potential solutions.

At school level, timetabling and collaborative planning opportunities need to be provided for teachers of contributory disciplines to work together.

Above all, if examination and accountability systems do not embrace and assess STEM (and STEAM) in ways which promote STEM competence and literacy (including the kinds of knowledge, skills, values and attitudes outlined in this paper) then integrated multi-disciplinary and transdisciplinary approaches will remain aspirational and elusive.

CONCLUSION

As transport, telecommunication gadgets and the internet shorten the 'social distance' and travelling time between people and different parts of the globe, the world is getting smaller. Similarly, as the 4th Industrial Revolution gains momentum and influences our everyday life in unprecedented and unanticipated ways, the boundaries between STEM and non-STEM areas are blurring. With quantum-leaps in digitalisation and artificial intelligence, technology is changing the way we live our lives and forcing a rethink the traditional segregation of knowledge and skills in STEM and non-STEM fields. STEM and non-STEM fields may differ in origin and orientation but the aims, skills, attitudes and values they promote are essentially the same. The time for a competence-based curriculum has come, in which STEM has an important but not exclusive role.

We need to identify and make explicit the competences that the younger generation require to live a sustainable and healthy life in the 21st century. This agenda requires consideration of all areas of the curriculum including the Arts broadly, and the Physical and Social Sciences which bring important humanistic and aesthetic dimensions to STEM challenges, processes and solutions.

Educationists need to come together in search of a synergy among and across the various traditional subject groups in school curricula. Teachers' capacities, infrastructure and resources need to be developed. We need to engage society and wider professionals in this endeavour. We should acknowledge differences but, at the same time celebrate and consolidate similarity and strike the right balance for the greater good.

APPENDIX

Appendix 1: Big Ideas of Science (Harlen, 2010, 2015)

- All matter in the universe is made of very small particles
- Objects can affect other objects at a distance
- Changing the movement of an object requires a net force to be acting on it
- The total amount of energy in the universe is always the same but can be transferred from one energy store to another during an event
- The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate.
- Our solar system is a very small part of one of billions of galaxies in the universe
- Organisms are organised on a cellular basis and have a finite life span
- Organisms require a supply of energy and materials for which they often depend on, or compete with, other organisms
- Genetic information is passed down from one generation of organisms to another
- The diversity of organisms, living and extinct, is the result of evolution

Other than the above 10 big ideas of science concepts, 4 big ideas about science are also listed (Harlen, 2010; 2015):

- Science is about finding the cause or causes of phenomena in the natural world
- Scientific explanations, theories and models are those that best fit the evidence available at a particular time
- The knowledge produced by science is used in engineering and technologies to create products to serve human ends
- Applications of science often have ethical, social, economic and political implications

Appendix 2: Big ideas in Mathematics (Randall, 2005)

- NUMBERS — the set of real numbers is infinite, and each real number can be associated with a unique point on the number line.

- THE BASE TEN NUMERATION SYSTEM — The base ten numeration system is a scheme for recording numbers using digits 0-9, groups of ten, and place value.

- EQUIVALENCE: Any number, measure, numerical expression, algebraic expression, or equation can be represented in an infinite number of ways that have the same value.

- COMPARISON: Numbers, expressions, and measures can be compared by their relative values.

- OPERATION MEANINGS & RELATIONSHIPS: The same number sentence (e.g. 12-4 = 8) can be associated with different concrete or real-world situations, AND different number sentences can be associated with the same concrete or real-world situation.

- PROPERTIES: For a given set of numbers there are relationships that are always true, and these are the rules that govern arithmetic and algebra.

- BASIC FACTS & ALGORITHMS: Basic facts and algorithms for operations with rational numbers use notions of equivalence to transform calculations into simpler ones.

- ESTIMATION: Numerical calculations can be approximated by replacing numbers with other numbers that are close and easy to compute with mentally. Measurements can be approximated using known referents as the unit in the measurement process.

- PATTERNS: Relationships can be described and generalizations made for mathematical situations that have numbers or objects that repeat in predictable ways.

- VARIABLE: Mathematical situations and structures can be translated and represented abstractly using variables, expressions, and equations.

- PROPORTIONALITY: If two quantities vary proportionally, that relationship can be represented as a linear function.

- RELATIONS & FUNCTIONS: Mathematical rules (relations) can be used to assign members of one set to members of another set. A special rule (function) assigns each member of one set to a unique member of the other set.

- EQUATIONS & INEQUALITIES: Rules of arithmetic and algebra can be used together with notions of equivalence to transform equations and inequalities so solutions can be found.

- SHAPES & SOLIDS: Two- and three-dimensional objects with or without curved surfaces can be described, classified, and analyzed by their attributes.

- ORIENTATION & LOCATION: Objects in space can be oriented in an infinite number of ways, and an object's location in space can be described quantitatively.

- TRANSFORMATIONS: Objects in space can be transformed in an infinite number of ways, and those transformations can be described and analyzed mathematically.

- MEASUREMENT: Some attributes of objects are measurable and can be quantified using unit amounts.

- DATA COLLECTION: Some questions can be answered by collecting and analyzing data, and the question to be answered determines the data that needs to be collected and how best to collect it.

- DATA REPRESENTATION: Data can be represented visually using tables, charts, and graphs. The type of data determines the best choice of visual representation.

- DATA DISTRIBUTION: There are special numerical measures that describe the center and spread of numerical data sets.

- CHANCE: The chance of an event occurring can be described numerically by a number between 0 and 1 inclusive and used to make predictions about other events.

Appendix 3: Big ideas in engineering habits of thinking (Royal Academy of Engineering, 2014; Institution of Mechanical Engineers, 2016)

- Testing, rethinking, changing
- Making things better through experimenting, designing, sketching
- Generating ideas and solutions as creative problem solvers
- Seeing connections between things, seeking out patterns
- Visualising or moving from abstract ideas to concrete
- Deciding what is the actual question, finding out if solutions already exist

Appendix 4: Core disciplinary ideas in STEM (National Research Council, 2012)[2]

SEVEN CROSS-CUTTING CONCEPTS OF THE FRAMEWORK:

1. Patterns. Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.

2. Cause and effect: Mechanism and explanation. Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.

3. Scale, proportion, and quantity. In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.

4. Systems and system models. Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.

5. Energy and matter: Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.

6. Structure and function. The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.

7. Stability and change. For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.

[2] National Research Council. 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, The National Academies Press, p. 84.

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