Integrated STEM Education: Promoting STEM Literacy and 21st Century Learning

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INTRODUCTION

Rapid changes such as emergence of k-economy, scientific and technological innovation, and advances in information and communication technology (ICT) are visibly experienced in the 21st century. These changes are interconnected and our world is becoming more complex as these changes continues to increase. The complexities of today's world require all people to be equipped with a new set of core knowledge and skills to solve difficult problems. In fact, the global changes has also changed the skills needed for success in the workplace. As widely discussed in the literature, 21st century workplace emphasizes on human capital which are knowledgeable and able to apply knowledge to generate innovations that can contribute to the betterment of society and the improvement of the nation's wealth. In addition to knowledge, innovation in the 21st century requires a new range of skills known as 21st century skills. For instance, effective communication and collaboration problem solving skills are part of the 21st century skills. Increasing levels of complexity require expertise communicate effectively and work collaboratively with people from all over the world to solve problems or create novel products. 21st century skills enable one to navigate successfully in the more complex and competitive life and work environment in the 21st century (Partnership for 21st Century Skills, 2009).

These changes imply that science, technology and innovation are now key for greater social well-being and economic growth. Furthermore, the complexities of today's world require all people to be equipped with science, technology, engineering and mathematics (STEM) knowledge and 21st century skills to solve most problems that are interdisciplinary in nature. Education is the foundation of human capital development, thus school needs to produce students who are STEM-literate and competent in the 21st century skills to become science and technology innovators and remain competitive in the 21st century labour market.

This is highlighted by the CEO Forum on Education and Technology (2001) that the definition of student achievement in the 21st century must be further expanded to include the 21st century skills.

In the Malaysian context, the science and technology innovation has been recognized as essential engine of economic growth to strengthen Malaysia's global competitiveness as well as to propel Malaysia into an innovative nation and achieve the goals of Vision 2020. According to the Science and Technology Human Capital

Roadmap (STHCR) 2020, Malaysia requires 500000 science and technology human capital in 2020 (MOSTI, 2012). Therefore, Malaysia needs to ensure the supply of human capitals who have mastered the knowledge of STEM and 21st century skills to support science and technology innovations.

In line with the current global changes as well as the national vision and mission, Malaysia has instituted the 60:40 (Science/Technical: Arts) Policy to increase the number of science-stream students. The increase in enrolment, however, should be followed by an increase in the students' STEM literacy and 21st century skills. STEM literate students will be capable of identifying, applying, and integrating the STEM concept to understand complex problems and generate innovation to solve the problems (Chew, Noraini, Leong & Mohd Fadzil, 2013). STEM literacy plays an important role in human daily lives in this era since they are many issues related to science and technology. Meanwhile, the 21st century skills are needed to enable students to face challenges of work and life the 21st century (Kamisah, Shaiful Hasnan & Arba'at, 2009).

Henceforth, science education in Malaysia should be shifted to the integration of the acquisition of knowledge and inculcation of 21st century skills to ensure that students are well-equipped with knowledge, skills and values essential to the 21st century everyday life and workplaces productivity.

To contribute towards enhancing the quality of the 21st century human capital, STEM education and 21st century learning have been introduced by the Ministry of Education. Since that, acronym STEM and 21st century classroom have been widely discussed among teachers. However, an understanding of STEM education and 21st century learning vary especially among science and mathematucs teachers. When hearing the term "STEM" and "21st century learning", many conjure images of classrooms equipped with ICTs or using technologies to teach STEM subjects. Others think of teaching students about technology. As a results, some schools started equipping classrooms with computers/smart boards, and began organising apps/robot/software designing courses for students. Moreover, some of teachers do not realize the interconnection of the STEM education and 21st century learning.

Both are seen as two different approaches with different purposes. In short, teachers still pose important questions about how to move STEM education and 21st century education forward.

They struggle to provide students with meaningful STEM experiences that promote 21st century learning. 21st century learning is typically used to describe the types of competencies needed to thrive in today's complex and interconnected global landscape (Bernhardt, 2015).

The inability to understanding meaningfully both STEM education and 21st century learning seems to be the main weakness of many teachers. We believed that this might due to lack of relational understanding – a more meaningful learning. There are generally two different types of understanding: Relational understanding refers to the process of knowing both what to do and why, and instrumental understanding describe the process of knowing rules without reasons (Skemp, 1978). It is a widely-held perception and belief that teachers who understand relationally are more likely to connect new learning with previous learning. However, many Malaysian in-service teachers were taught instrumentally during short-term (one-to five-day) or one-off training courses because given such a limited time. As Orchard and Winch (2015) highlighted, teachers rely on philosophical ideas or theory to make good professional judgments in addition to subject knowledge and technical know-how. For instance, teachers must understand key educational concepts and principles that underpin various practices in order to be able to explain and justify their judgments to pupils, parents and other stakeholders. If they just understand instrumentally, they will be operating as mere technicians. Therefore, in this paper we discuss (1) the theoretical foundations of STEM education, and (2) the guiding principles STEM education that promote STEM literacy and 21st century learning. In addition, we also presents the outline of instructional activities based on the STEM guiding principles.

THERORETICAL FOUNDATIONS OF STEM EDUCATION

STEM education is drawn upon two important theories in learning and education which are constructivism and constructionism. The former focuses on the role of students as builders of meanings and ideas while the latter added that the building of new ideas occur best through constructing real-world artefacts.

Constructivism

Constructivist theory focuses on the role of students as knowledge builders. Among the major theories that contribute to the growth of constructivism include Piaget, Vygotsky and Bruner's theories of learning.

Piaget's theory explains how humans organize information into the cognitive structure and explains how cognitive development occurs. According to Piaget, the new information is organized into existing cognitive structures (schemata) through two cognitive processes, namely assimilation and accommodation. Piaget (1970) asserted that assimilation does not occur without accommodation and vice versa. In other words, assimilation and accommodation are two complementary processes. Piaget also introduces the process of 'increasing equilibration' as key mechanism in cognitive development. This process requires equilibrium between assimilation and accommodation (Piaget, 1970, 1977) to seek for better equilibrium through cycles of equilibrium, disequilibrium and re-equilibrium. Equilibration therefore is a dynamic process. According to Piaget (1977), conflict situations can be created to attain the goal. This means that cognitive development occur when disequilibrium or cognitive conflicts are resolved (Schunk, 2012). The process of equilibration aims to restore equilibrium or resolve conflicts through the processes of assimilation and accommodation which are complementary.

Other aspects in the constructivist theory include learning can be enhanced through social interaction and discovery. Vygotsky (1978) believed that learning is influenced by the social environment and emphasized on the role of social interaction in learning and cognitive development. Collaboration between students with teachers or peers provides scaffolding to students in the Zone of Proximal Development to help them construct knowledge. Meanwhile Bruner (1966) believed that learning and problem solving are the result of the exploration of new knowledge. If students discover knowledge and the relationships on their own, they will gain a deeper understanding (Bruner, 1962).

Briefly, the constructivist theory states that students do not receive knowledge passively, but he/she interpret the knowledge received and then modify the knowledge in a form that acceptable to him/her. In other words, individual student actively constructs new knowledge pursuant to his/her existing knowledge. Construction of new knowledge can be improved through social interaction. Through social interaction, triggering of cognitive conflict and restructuring of ideas will occur when students share their ideas from their own perspective. However, no interaction would be beneficial if new knowledge is presented to students traditionally. Instead, student should be given the opportunity to explore new knowledge.

Constructionism

The theory of constructionism is built on the theory of constructivism which defines learning as knowledge construction in the student's mind. In addition to the constructivist theory, constructionist theory of learning asserts that the construction of new knowledge happen felicitously in a context where students are consciously involved in the production of external and sharable artefacts (Papert 1991). This theory emphasizes the role of design (making, building or programming) (Kafai & Resnick, 1996) and external objects (Egenfeldt-Nielsen, 2006) in facilitating the knowledge construction. In this process, the designers (or students) create artefacts which are significant to themselves based on their interests, learning styles and their experience, and shares their artefacts as well as the artefacts' designing process with others.

The constructionist theory of learning goes beyond the idea of learning-by-doing as indicated by Papert (1999a) that 'I have adapted the word constructionism to refer to everything that has to do with making things and especially to do with learning by making, an idea that includes but goes far beyond the idea of learning by doing'. Indeed, Papertian constructionism challenges the student applying the knowledge being explored to construct more complex ideas or larger theory. In this process, students' knowledge serves as 'instrument of personal power' (Papert 1980). Thus, traditional curriculum model that uses themes and projects as a way to help students learn a particular knowledge or skill (Figure 1) should be flipped (Figure 2) to allow students to use their knowledge and skills to complete a theme-based project. (Stager 2005).

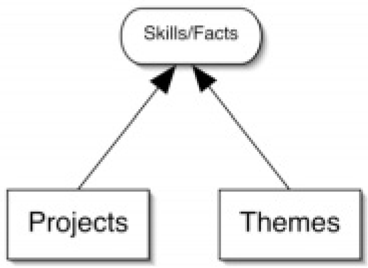

Figure 1. Traditional Curriculum Model

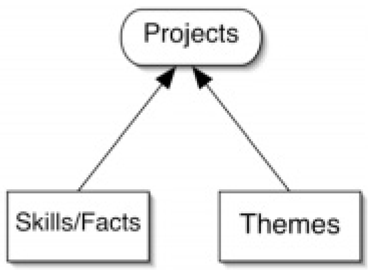

Figure 2. Constructionist Curriculum Model

Source: Stager (2005)

Computers play a role in the constructionist learning theory. Computers can be used as a building material (Papert, 1999a) as well as a 'material to be messed about with' (Papert & Franz, 1988). Learning occurs when students are 'messing about' with the computer. The introduction of computers is also able to change the context of learning (Papert, 1991). Computers can serve as a convivial tool (Falbel, 1991). The willingness of students to learn will increase because they can use the computer in building artefacts (Papert, 1991). Papert (1980) has described that 'The computer is the Proteus of machines. Its essence is its universality, its power to simulate. Because it can take on a thousand forms and can serve a thousand functions, it can appeal to a thousand tastes'. However, he stressed that the main focus is not on the computer but on the minds of students (Papert, 1980). Additionally, constructionist theory also values the diversity of learners and social aspects of learning. According to Kafai dan Resnick (1996), this theory recognizes that learners can build relationship with knowledge through various ways, and community members can act as collaborators, coaches, audiences and co-constructors of knowledge in the constructionist learning environment.

In summary, constructionism proposed that learning can be enhanced if students are involved in collaborative artefact designing projects using digital tools as construction material. Furthermore, students should be encouraged to create prototypes or artefacts from their own ideas. Principles derived from the constructivist and constructionist learning theories are summarized in Figure 3.

1. Knowledge reconstruction: Student constructs new understanding pursuant to his/her existing knowledge.
2. Collaboration: Peer collaboration may trigger cognitive conflict and this may result in reconstruction of ideas.
3. Exploration: Understanding is lifted when students discover new knowledge themselves.
4. Problem solving: New understanding occurs when students discover their own solutions to a problem or a task.
5. Learning through designing: Learning can be enhanced if students are involved in artefact designing projects. Design projects are often interdisciplinary, bringing together knowledge from STEM subjects as well as other disciplines.
6. Construction: Students are challenged to apply what they have learned to construct more complex ideas or larger theory.
7. Technological literacy: Use technology efficiently and effectively to achieve specific goals. Students must be technologically literate to live, learn, and work successfully in today's Digital Age.

Figure 3. Principles of Constructivist and Constructionist Learning

PRINCIPLES OF STEM EDUCATION

Based on constructivist and constructionist learning theories as well as literature analysis, we identified 11 guiding principles that should be incorporated in STEM education:

1. STEM education should contribute towards cultivation of STEM-literate citizenry.

STEM literacy is important both inside and outside STEM fields. Therefore, STEM education should aim to equip students with knowledge, skills and values that are relevant to the 21st century workplace and everyday life. These students will be qualified human capital in STEM-related careers. They will be able to make judicious decisions to invent new technologies to solve various problems in today's world. This is also important for those who never directly pursue STEM-related careers. They will be able to apply the skills that come from studying STEM subjects in solving many problems in their daily life which is dominated by science and technology.

2. STEM education should emphasize development of students' 21st century skills.

The CEO Forum on Education and Technology (2001) and Partnership for 21st Century Skills (2009) have proposed that students' achievement in the 21st century should be expanded further and emphasis should be given simultaneously on improving academic achievements and the 21st century skills. Kamisah and Neelavany (2010) have identified five important clusters of 21st century skills which need to be integrated in the Malaysian science curriculum, namely (1) digital age literacy, (2) inventive thinking, (3) effective communication, (4) high productivity, and (5) spiritual values.

3. STEM education should emphasize multidisciplinary or integrated approach

This may include exploring approaches to tackling global grand challenges of the 21st century such as health, energy efficiency, natural resources, environmental quality and hazard mitigation (Bybee, 2010). STEM disciplines are interrelated (Balaban & Klein, 2006). However, STEM subjects are taught in silo traditionally. Besides, science and mathematics have been emphasized more than engineering and technology in primary and secondary levels. Infusing technology and engineering into science and mathematics learning can cultivate deeper understandings and better development of skills than learning the subjects in isolation (Bryan et al., 2016). Thus, emphasis should be given on providing students with high-quality interdisciplinary STEM learning experiences to solve real-world problems. These problem may include exploring approaches to tackling global grand challenges of our era, such as health, energy efficiency, natural resources, environmental quality and hazard mitigation (Bybee, 2010).

Integrated STEM should mean application and integration of engineering practice with the content and practice of science and mathematics (as well as other disciplines) to design technologies that solve real-world problems through collaboration and communication. In this regard, the engineering practice serve as an integrator – bind together science and mathematics content and practices, as well as meaningfully bring in other disciplines, to produce technologies for a specific purpose (Bryan et al., 2016; Moore et al., 2014).

4. STEM education involved designing shareable technologies, leveraging technologies, and developing technological literacy.

The applications of scientific knowledge and practices to engineering have contributed to the technologies and the systems that support them that serve people today (National Research Council, 2012). ITEA (2000) defines technology as "the innovation, change, or modification of the natural environment in order to satisfy perceived human wants and needs".

Clearly, technology means innovation or products (a single device or a complex systems) that solve problems and extend human capabilities. Design projects are often interdisciplinary, bringing together knowledge from STEM subjects as well as other disciplines. Contemporary technologies such as ICT can be leveraged to communicate, collaborate, solve problems, accomplish tasks and as construction material. However, the focus of integrated STEM is not on the technology alone, but on the fostering innovation and invention as well as promoting technological literacy. Technological literacy is beyond knowledge and application of ICT.

5. STEM education should emphasize collaboration and communication.

Collaboration and communication are two important 21st century skills (Binkley et al., 2012; NCREL & Metiri Group, 2003; Partnership for 21st Century Skills, 2009). Students should be given opportunities to engage in collaborative problem solving or task. Taking part in collaborative task may deepen students' understanding as cognitive conflict may be triggered during activities and hence, new understanding may discover. Moreover, students should be encouraged to use real-world tools (e.g., digital cameras and digital video cameras) to communicate their ideas. Besides, they should be encouraged to communicate information or ideas effectively in multiple format (orally, graphically, textually, etc.). Limiting student expression to pencil and paper makes the demonstration of understanding difficult for many students. Contemporary tools can play a facilitative role in effective collaboration and communication.

6. Integrated STEM education should engage students in argumentation through scientific argumentation and design justification

Just like STEM professionals, students be engaged in learning through inquiry. The process of inquiry required students to engage in argumentation for a claim or decision. Argumentation invites diverse opinions from peers with justifications for their claims. In this process, students make claims based on evidences, listen to input from peers and defend their claims using well-reasoned justifications. Peer's input may guide them towards restructuring existing idea and hence towards deeper level of understanding.

In design activity, engineers collaborate to gather opinions for better solution. Argumentation is used to justify their design decision and explain design process (Baek, Koh, Cho, & Jeong, 2015). Justification of design choices is parallel to the argumentation in science education (Bryan et al., 2016). Bryan et al. (2016) also pointed out that design justification is one way to require the students to apply the science and mathematics to the engineering design. This learning experiences provide opportunities for student to deepen science and mathematics content knowledge as well as engineering thinking or 'habits of mind' (values, attitudes, and thinking skills associated with engineering). Engineering 'habit of mind' align with 21st century skills such as systems thinking, creativity, optimism, collaboration, communication, and ethical considerations (Katehi, Pearson, & Feder, 2009).

7. STEM education should incorporate practices of STEM professionals to develop students' understanding of the nature of science, technology, engineering and mathematics.

Practices are behavior that STEM professionals engage in as they investigate, design and problem solve, as well as build models, theories and systems (Bryan et al., 2016). Practices involve the use of both discipline knowledge and skills specific to each practice (NGSS Lead States, 2013). The practices of STEM professionals includes scientific inquiry, mathematical thinking, and engineering design and engineering thinking. Repeated opportunities engaging in STEM professionals' practices contributes to better understanding of the nature of science, technology, engineering and mathematics. We believed that developing understanding of the nature of science, technology, engineering and mathematics is necessary for STEM literacy for the same reasons that understanding of nature of science and mathematics is a pre-requisite for increasing science literacy and mathematics literacy (Lederman, Lederman, & Antink, 2013; Ojose, 2011)the primary rallying point for science education reform is the perceived level of scientific literacy among a nation's populace. The essential nature of scientific literacy is that which influences students' decisions about personal and societal problems. Beyond this, however, educators work to influence students' ability to view science through a more holistic lens. Examining the philosophy, history, and sociology of science itself has the potential to engender perceptions of science, in the broader context, that can impact the lens through which students view the world. The integration of explicit, reflective instruction about nature of science (NOS).

8. Finally, students are expected to build new solutions or construct more complex ideas or larger theory by leveraging of STEM knowledge and practices as well as 21st century skills and resources. In other words, they become creative problem solvers, innovators and inventors.

IMPLEMENTATION

Based on the constructivist and constructionist learning theories, the IDPCR phases (i.e. Inquiry, Discover, Produce, Communicate and Review) were designed and developed to assist students in carrying out both inquiry and design activities. The IDPCR phases are derived from the BSCS 5E Instructional Model (Bybee et al., 2006) and Creative Design Spiral (Rusk, Resnick, & Cooke, 2009). It is expected that the acronym IDPCR can help students remember the five important domains of 21st century skills, i.e. Inventive thinking, Digital-age literacy, high Productivity, effective Communication and spiritual values (nilai keRohanian). The five domains of 21st century skills have been identified by Kamisah and Neelavany (2010). It is important to point out that the IDPCR phases do not always follow in order. For instance, at any phase, students can communicate information or findings to people from many different backgrounds and specialties to gain input from them. They are also encouraged to communicate in groups and report back with their findings at any phase.

The authors also recognise that the IDPCR phases may be too wordy and abstract for young learners. For young learner, the phases may be reduced to four phases and replace the abstract words with Think, Make, Communicate and Improve (TMCI). The TMCI model is derived from the TMI (Think, Make, Improve) Model (Martinez & Stager, 2013). In our model, 'communicate' is added and made explicit as communication is a fundamental practice of science and engineering (NGSS Lead States, 2013). Communication is also recognised as one of the important 21st century skills.

Table 1.The IDPCR and TMCI Phases, and Related Phases of the BSCS 5E Instructional Model, Creative Design Spiral, and the Science and Engineering Practices.

TMCI	IDPCR	BSCS 5E Instructional Model	Creative Design Spiral
Think	Inquiry	Engage	Imagine
	Discover	Explore	Experiment
Make	Produce	Elaborate	Create
Communicate	Communicate	Explain	Share
Improve	Review	Evaluate	Reflect

In the following section, the authors present the outline of instructional activities based on the STEM guiding principles. The instructional activities were designed to engage students in practices of STEM professionals.

Table 2. Outline of Instructional Activities

IDPCR Phase	Purpose	Inquiry Activity	Design Activity
Inquiry *Predict, ask, hypothesize, identify problem, brainstorm*	1. Arouse students' interest 2. Access students' prior knowledge 3. Elicit students' misconceptions 4. Clarify and exchange current conceptions	1. Teacher shows discrepant events. 2. Students ask questions about the phenomena they observe. 3. Students explain the phenomena at the sub-microscopic and symbolic levels. 4. Students develop and/or use models to describe and/or predict phenomena. 5. Students discuss in groups and compare their ideas with their peers. 6. Students do background research by obtaining and evaluating information from various sources.	1. Students define the problem to be solved and to elicit ideas that lead to the constraints and specifications for its solution. 2. Students do background research by obtaining and evaluating information from various sources. 3. Students brainstorm ideas to develop as many solutions as possible. 4. Students convey possible solutions through visual or physical representations. 5. Students develop models to represent events or possible solutions.
Discover *Investigate, experiment, explore*	1. Expose to conflicting situations 2. Modify current conceptions and develop new conceptions 3. Provide opportunities for students to demonstrate their conceptual understanding, and skills	1. Students formulate hypothesis and identify variables. 2. Students plan and perform investigation in groups. 3. Students analyse and interpret data, and draw conclusion. 4. Students use mathematics and computational thinking. 5. Students use laboratory tools connected to computers for observing, measuring, recording, and processing data. 6. Students engage in discussions and information seeking using ICT or talking to experts. 7. Students practise the skills needed in scientific investigations. 8. Students communicates in groups and report back with their findings.	1. Students selecting a promising solution. 2. Students plan and create prototype. 3. Students test the prototype and redesign prototype as necessary. 4. Students analyse and interpret data. 5. Students use mathematics and computational thinking. 6. Students use laboratory tools connected to computers for observing, measuring, recording, and processing data. 9. Students engage in discussions and information seeking using ICT or talking to experts. 7. Students practise the skills needed in engineering design activities. 8. Students communicates in groups and report back with their findings. 9.

Produce *Create, construct, invent, build, design, tinker, elaborate*	1. Challenge and deepen students' conceptual understanding and skills 2. Provide additional time and experiences that contribute to the generation of new understanding	1. Students generate explanation for the causes of phenomena supported by evidences consistent with STEM knowledge. 2. Students develop and/or use models to describe phenomena. 3. Students apply their new ideas by conducting additional activities that are more complex and involve HOTS. 4. Students apply new idea and develop technologies to solve problems based on IDPCR or TMCI phases.	1. Students create final prototype based on data from testing. 2. Teacher reminds students of the basic steps of the engineering design process. This is a cyclical process that requires innovators to test and redesign creations as often as it takes so that they end up with reliable finished products. 3. Students generate explanation for the design solution supported by evidences consistent with STEM knowledge.
Communicate *Explain, share, discuss with peers, ask an expert, defend*	1. Provide opportunities for students to share their new understanding and skills 2. Provide opportunities for students to exchange their new understanding	1. Students communicate their ideas, process and new findings through oral presentation. 2. Students summarize complex evidence, concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms. 3. Students engage in argument from evidence. 4. Students use real-world tools and multiple formats to communicate information or ideas. 5. Students also listen to input from peers and defend their ideas. Peer's input may guide them towards deeper level of understanding. 6. Students compare their ideas with the teacher's explanations.	1. Students communicate their design, process and solution through oral presentation. 2. Students summarize complex evidence, concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms. 3. Students engage in design justification or argument from evidence. 4. Students use real-world tools and multiple formats to communicate information or ideas. 5. Students also listen to input from peers and defend their ideas. Peer's input may guide them towards deeper level of understanding. 6. Students compare their designs.
Review *Check, evaluate, reflect, improve, repair*	1. Students assess their understanding, skills and competencies 2. Students think creatively for the purpose of improvement 3. Teachers evaluate student progress	1. Students reflect upon the extent to which their understanding, abilities and competencies have changed. 2. Students reflect on the practices of science and engineering. 3. Students improve their ideas or skills based on reflection or input from peers. 4. Teacher conducts tests to determine the level of	1. Students describe the key strengths and weaknesses of their designs. 2. Students improve their prototype in groups that incorporates the best aspects of all the designs, as well as improvements suggested through testing. 3. Students reflect upon the extent to which their understanding, abilities and competencies have changed.

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