

## The Necessity of Computational Thinking in STEM Education: An Analysis with Recommended Research

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### Abstract

*In this digital era, implementations of technology in classroom are still in a worrisome state especially in Science, Technology, Engineering and Mathematics (STEM) education. Integrating computational thinking (CT) into STEM education allows the technologies to be a part of STEM education that can produce students with advance skills in technology as well as better equipped with the necessary knowledge as a STEM students. This article examines the needs of CT in STEM education and the relationship between CT and STEM education. This review paper was conducted involving systematic review and meta-analysis of CT elements in STEM education conducted as well as literature research of archival records of selected published articles, documents and journals. Only peer-reviewed journals from databases subscribed by the researchers' university including Science Direct, Scopus, Web of Science, and SpringerLink Journal were selected using keywords related to CT, and STEM. Analysis from these sources has revealed that CT is necessary in STEM education because: (1) CT concepts are relevant with STEM; (2) CT and STEM can be applied at all levels; (3) CT can assist in project-based learning in STEM education; (4) CT facilitates clearer understanding of STEM content; and (5) CT promotes the development of multiple skills at once. These findings are discussed and recommendations for future researches.*

**Keywords:** Computational thinking (CT); STEM education; CT tools; CT concepts

### Introduction

#### Background and Overview

Computer is a technology that is important in the digital era. As a tool to make life easier, computer can be used to perform various tasks including develop a website, writing, and calculating numbers. With the help of computer, problem solving can be done with ease and can be presented in a clear and compelling form. In this digital age, a child with an ability to solve problems in systematic manner like how a computer would do is highly desirable. Due to its ability in making life more effective, easier, and practicable, computational thinking (CT) is needed in all students regardless of their age and field, thus has becoming a part of teaching and learning in classroom (Czerkawski & Lyman, 2015). Furthermore, CT has another benefit; it revolutionized the way human think (Bundy, 2007). These attributes has led many researchers to study CT skills and investigate on how current and future generation could utilize this skills as a preparation for the upcoming future.

One of the issues with CT is undefined and generally acceptable definition of CT, thus causing misconception and inconsistencies (Barr, Harrison & Conery, 2010; Selby & Woollard, 2013). Most people relate CT with computer science field, however CT can also be applied in mathematics and engineering field, as it was initially meant to be a part of Science, Technology, Engineering, and Mathematics (STEM) education (Wing, 2006). CT skills are dependable on the studied field, not just exclusive to the field of science (Berland & Lee, 2011). Based on this statement, CT can be said to be dynamic as it can be applied in many fields using specific CT elements on that particular field.

## **Rationale and Objectives**

In Malaysia, CT is defined as “a process of problem-solving done either by human alone or using machine or both based on the basic concept in computer science”. According to Ministry of Education Malaysia (MOE), CT is “a process to solve problems by using logic in terms of the problems’ nature, obtained data, and following standard procedure to achieve target goal”. Therefore, CT is a thinking skills set and a process in formulating and finding solution to a problem with or without the aid of a technological device and presented in a comprehensible form.

The concepts of CT as proposed by Selby and Woollard (2013) (i.e. decomposition, pattern recognition, abstraction, evaluation and algorithm thinking) have strong relationship with STEM education as revealed from the study by Swaid (2015). STEM education emphasised on combination of learning with real-life situation in a classroom setting. Moreover, computational utilization in STEM disciplines is high in these fields thus CT is integral for STEM education (Foster, 2006; Henderson et al, 2007). However, efforts in implementing e-science in STEM education is less than expected despite numbers of e-science system currently developed (NSF, 2013). Furthermore, to sustain continuous discovery, thinking skills set among STEM educators and students must be developed (Swaid, 2015). Thus, there is a need for a research that focuses on CT in STEM education that is given emphasis by the Ministry of Education (MoE) Malaysia. Therefore, the main objectives of this paper are to review the impact and outcomes of integrating CT into STEM education; as well as how CT can become a necessary skill as a part of STEM education.

## **Literature Review**

### **Computational Thinking**

In early years, CT is defined as “an intellectual skill set and thinking on how an individual interact and think by using computer language” (Wing, 2006). As a rising thought process for the 21<sup>st</sup> century generation, CT is “a thinking process to formulate and solve problems in a systematic manner like any computer devices would do” (Cuny, Synder & Wing, 2010). CT requires thinking at multiple level of abstraction using computational concepts in tackling a problem (Wing, 2006). Many researchers in education are starting to take interest in CT due to its applicability in fields such as science and humanitarian field (Bundy, 2007).

To understand CT’s capability and the concept of CT including its specific skills, CT definition is needed. However, it has been reported by Guzdial (2008) that there is no clear definition, thus researchers interested in this area have to define CT according to the field of their study. One general consensus on definition of CT was from Wing (2006); “CT is a thought process

in formulating problems and it is a solving method that can be represented in an effective form just like how machines do” (Wing, 2006). The concept of CT in education is to train students to think like scientist majoring in computer is thinking, in which the students solve the problems in a way a computer could (Shuchi & Roy, 2013). As a thinking process, CT is used to formulate a problem and finding its solutions, so that, the solution can be represented in a form that can be executed by information processing agent (Bundy, 2007; Wing, 2006; Selby, 2014). Simply put, CT is a process in which problems can be solved systematically and is expressed in a way a computer can which is important in the learning of mathematics and science. There are 5 main concepts in CT as proposed by Selby and Woolard (2013); (i) decomposition, (ii) pattern recognition, (iii) abstraction, (iv) evaluation, and (v) algorithm thinking.

## **STEM Education**

STEM is an acronym for Science, Technology, Engineering and Mathematics. Initially arranged as SMET, the acronym was reconstructed into STEM due to its non-familiar and unattractive word (Sanders, 2009). The National Research Council [NRC] (2014) defined STEM education as an integrated set of fields of Science, Technology, Engineering and Mathematics instructions, combining classroom learning with real-world experiences. This educational approach provide students with both technical as well as personal professional skills in order to be a skilled worker by integrating and teaching them the knowledge and skills in classroom to apply in real world situation.

According to Malaysia Education Blueprint 2013-2015 (Ministry of Education, 2012), STEM education is the government’s initiative to produce skilful students who can face the challenges in science and technology fields in this competitive world. Moreover, the Ministry of Education Malaysia (MOE) has identified factors that caused the decreasing trend of students’ enrolment in STEM education. Thus, in order to attract more students on STEM education, MOE has introduced the new primary and secondary curricula with some aid of ICT-based-technology for teaching and learning session. The decreasing number of students’ enrolment in STEM disciplines is at a worrisome state and is not only happening in Malaysia, but in other countries too. For example in America, according to Diaz and King (2007) there are few students graduated from high school who are fully aware and interested in degree program or a career involving any disciplines in STEM fields.

Students should be exposed in practicing solving problems and making decisions instead being built as a “warehouses” of facts collection (Kolodner et al., 2013). The decline in students’ enrolment in STEM disciplines might be due to science education’s failure in initiating students’ passion and interest by separating these attributes from daily activities. Thus, the authorities have to consider about the reformation and reconstruction of the education system and the curriculum to produce students who have all necessary skills to face the challenges in this digital age. With proper teaching materials, relevant and attractive activities conducted in classroom, students’ motivation to learn will increase which also increases their knowledge and skills that can be used for future problems (Diaz & King, 2007). Furthermore, igniting students’ interest on the subjects will open a possibility for them to select courses related to STEM programs and careers. Satchwell and Loepp (2002) stated that for students to feel motivated with their learning, they can be encouraged to construct their own knowledge of the world around them, and this objective can be achieved through integration of STEM projects. Despite multiple CT definitions, integrating CT with STEM education can helps students create better solution to a problem and discover new question (Lee et al., 2011). Thus, CT practices

with integration of STEM fields are important and relevant because of its promising outcomes for the students which have been shown by past researches.

### **Methodology**

This review paper was conducted involving systematic review and meta-analysis of CT elements in STEM education as well as literature research of archival records. Peer-reviewed journal articles were emphasised in order to complete the article within the time limit. The articles were searched using databases subscribed by the researchers' university including Science Direct, Scopus, Emerald Insight Web of Science, SAGE, and SpringerLink Journal using keywords related to CT, and STEM. In order to narrow down the search focus, the process of reviewing and categorization was employed, and the findings were analysed.

From the findings, the newest articles are mostly focusing on CT in computer science field and less on STEM education or any STEM related disciplines. There are studies on CT in STEM education, however the focuses were on CT tools in STEM education and discussions on the necessity of CT in STEM education are scarce. Therefore, past studies that implemented CT tools in interdisciplinary STEM fields were taken into consideration and elaborated using meta-analysis technique.

### **Results and Discussion**

The systematic review of literature through meta-analysis conducted revealed that there are five main areas which are important for STEM education and are elaborated in this section.

#### **Most CT Concepts are Relevant**

There is a correlation between CT concepts with introductory STEM courses before high school students enrol for a higher education level (Swaid, 2015). From the findings, the courses have huge impact on students' decision to further study in STEM education as these courses expose students with an introduction as well as providing information and understanding on STEM disciplines. Thus it is important to construct a plan that will deliver effective introductory courses that can attract high school students to choose STEM fields. Data reported by Swaid (2015) on the correlation between introductory courses of STEM with CT elements identified by the National Academies is summarised as shown in Table 1.

Table 1  
*Analysis of Computational Thinking Elements for STEM Courses*

STEM Courses	Computational Thinking Elements						
	Abstraction	Data	Retrieving	Algorithms	Design	Evaluation	Visualization
Biology I		/	/	/		/	/
Biology II		/	/	/		/	/
Applied CS	/	/	/	/	/	/	/
Programming I	/	/	/	/	/	/	/
Chemistry I		/	/	/		/	/
Chemistry II		/	/	/		/	/
College Algebra	/	/	/				/
Calculus I*	/	/	/				/
Calculus II*	/	/	/				/
Genetics		/	/	/			/
Programming Languages	/	/	/	/	/	/	/
Object-Oriented Programming	/	/	/	/	/	/	/

(Matsumoto & Cao, 2017; Swaid, 2015; Weintrop, et al., 2016)

Based on the analysis as shown in Table 1, we can clearly see that there are direct relationships between elements of CT with introductory STEM courses. The following are elaboration of meta-analysis based on the review of related literature. For example, in Chemistry I and II, there are 5 elements of CT related concepts and there are articles that explained how these CT concepts can be used in chemistry such as gas laws simulation. Integrating CT skills and CT tools in a classroom can make learning chemistry engaging (Weintrop et al, 2016). For instance, gas law simulation is an interactive and fun simulation that enables students to understand gas law reaction which is difficult to be done in real life (e.g. in classroom setting) because it is dangerous and requires huge amount of resources. Another study conducted using a CT tool, i.e. Microsoft Excel by Matsumoto and Cao (2017) was easy to use by educators and students. In the study, Microsoft Excel was used to manipulate variables on series of strong acid-strong base titration curves. CT tools give more advantage as an aid to be used on complex real-world situation without being engaged in extreme danger, wasting more resources and effort.

### **Computational Thinking and STEM are for All Levels**

The analysis of vast numbers of studies on implementation of CT in STEM education revealed that CT in STEM fields can be implemented (National Research Council, 2011; Repenning et al, 2010; Sengupta et al., 2013; Wilensky et al, 2014, Weintrop et al, 2015) to all educational level from primary education (Brennan & Resnick (2012) secondary education (Orton et al 2016), and even higher education (Aho, 2012). STEM education is slowly being implemented at all levels of education to promote and attract students so that they will choose a career with

STEM related learning or disciplines (Augustine, 2005). The following are the reviews with justifications made based on the abovementioned analysis:

1. The numbers of articles and journals on the application of CT at various levels of education that were found on the database, which showed that CT in STEM are rather flexible. For example, teaching and learning activities in pre-school nowadays are assisted with technology. This exposure towards technology at such a young age indirectly exposed the young students with CT skills. Kids aged 3 – 4 years are capable to use and manipulate computing devices despite their inability to read yet (Marcelino et al., 2018). Furthermore, science and mathematics has been introduced towards the young students since pre-school, which showed that the students have been exposed with CT skills and STEM disciplines as early as pre-school. Thus, the integration and application of CT in STEM can be further initiated and developed early on.
2. The study by Heintz, Mannila and Färnqvist (2016) about CT at primary and secondary education level in 10 countries including Europe, USA, Asia and Australasia revealed that the interest in CT skills among students are high. Most of these countries have already implement courses with computation approach despite differences in technology. This is an opportunity for policymakers and educators to integrate CT with courses related to STEM education.
3. Most people unable to relate CT with other disciplines other than computer science. Furthermore, due to diverse and confusing definition of CT, some education system has yet to introduce CT in the classroom (Czerkawski & Lyman, 2015). CT has three (3) dimensions; computational concepts, computational practices, and computational perspectives. Details of CT dimensions are summarised in the following Table 2.
4. A study on the effects of CT in higher education through mental models, programming tools, curriculum reform, and assessment has been conducted. From the study, introducing CT in higher education has many benefits regardless of their programs (science or non-science program), and preparing them for their working career and life styles (Garcia-Peñalvo & Mendes, 2017). Basically, CT gives benefit to the students in any fields and in all levels of education.

Table 2

*The Essential Skills Developed by Students under CT Concepts*

CT dimensions	Essential skills developed
1 Computational concepts	Coding in terms of its sequence, loops, events, and data
2 Computational practices	Using problem solving practices while coding; using various methods e.g. experimenting, iterating, testing and debugging
3 Computational perspectives	Understanding of self, of others and of the digital world

### CT Assists in Project-Based Learning of STEM Education

The third inference derived from the systematic review is that CT skills help students to reflect productively on STEM activities. These activities also help students to cultivate problem solving and logical thinking ability. For example, in one activity that requires students to make a robot that can move in a maze according to command, students engage in a problem-solving process. In this process, the students use skills such as decomposing a problem into sub-problems, and testing and debugging.



The process of obtaining genuine knowledge is through seeking answer to real-world problems which involves thinking within oneself; and in this case within the student him/herself. CT is one of the 21<sup>st</sup> century skills, and its goal is to teach and help individual to develop crucial skills in order to unravel a digitally and non-digitally problem-based in reality. With exposure of arrays of information, knowledge, and skills, with the aid of CT tools, students can solve problem and even able to manipulate the variables and applying by predicting problems that might happen in near future.

Activity involving CT and with the aid of CT tools teaches individual to seek answer to real-world problems by oneself. Furthermore, it helps the students to develop necessary skills to solve digital and non-digital problems, and even develop an ability to manipulate variables and predicting potential problems that could arise in the near future. STEM activities encourage students to learn more, motivate students and pique their interest as proven by a study conducted by Satchwell and Loepf (2002) on students' engagement towards STEM activities. The study has found that there is an increase in the students' scores on higher-level mathematical problem-solving and scientific process skills. It is clear that integrating CT in STEM's project-based learning showed positive impact on students' accomplishments, hence more studies on this matter should be done.

### **CT Facilitates Clearer Understanding of STEM Content**

Utilization of CT skills can help deepen students' learning on STEM content (Guzdial, 2008; The National Research Council, 2010; Repenning et al., 2010; Sengupta et al., 2013). These findings also concurred with the work of Fullan and Langworthy (2014) in which they concluded that technology should be used as a tool to support the pedagogy and this new partnership between pedagogy and technology enables deep learning in the students (pg. 32). Deep learning is a process in which the students are expected to be responsible of their own learning, and can be achieved through 'Learning-by-Doing'.

'Learning-by-Doing' enables the students to learn and apply their knowledge on the problems, thus improves their learning. This outcome can be achieved by integrating CT in STEM field. It is important to note that a stand-alone course in which the problems and application of CT are separated and an integrated CT in STEM are two different approaches. In order to motivate diverse participants in computational professions, a sense of real-world applicability is important (Margolis & Fisher, 2003). Thus, it is imperative to bring STEM and CT skills as a one body instead of two different entities to achieve desirable outcomes.

### **CT Promotes the Development of Multiple Skills at Once**

The fifth finding from this systematic review showed that holistic student can be developed through homogenization of CT and STEM education. Table 3 shows CT taxonomy and is further discussed in subsequent paragraphs. The taxonomy is divided into four (4) major categories; data practices, modelling and simulation software, computational problem-solving approach, and system thinking practices (Weintrop et al., 2016).

Table 3

*Computational Thinking in Mathematics and Science Taxonomy*

<b>Data Practices</b>	<b>Modeling and Simulation Practices</b>	<b>Computational Problem Solving Practices</b>	<b>System Thinking Practices</b>
Collecting data	Using computational models to understand a concept	Preparing problems for computational solutions	Investigating a complex system as a whole
Creating data	Using computational models to find and test solutions	Programming	Understanding the relationships within a system
Manipulating data	Assessing computational models	Choosing effective computational tools	Thinking in levels
Analyzing data	Designing computational models	Assessing different approaches/solutions to a problem	Communicating information about a system
Visualizing data	Constructing computational models	Developing modular computational solutions	Defining systems and managing complexity
		Creating computational abstractions	
		Troubleshooting and debugging	

(Weintrop et al., 2016)

These subsequent paragraphs discussed about activities that can be done in one of the categories in the taxonomy; data practice, in which these activities yield development of CT concepts.

1. The first activity is data collecting. A systematic data collection protocol is proposed by the students which they have to identify and construct a procedure on how to collect the data, and later presented using CT tools which are also related to algorithm concept of CT.
2. The second activity is data creating. Students come up with a systematic procedure and run a simulation. Through this activity, students able to describe the procedure and able to observe various outcomes through manipulation of variables (by adjusting the conditions for the simulation) which is directly related to pattern recognizing concept in CT.
3. The third activity is manipulation of data. Data is classified and sorted to its respective categories by fractionizing big data collection into small data based on similar characteristics of the data. This activity improve students' decomposition concept of CT.
4. The fourth activity was analysing data, where students generalized rules from the data and this activity will develop their evaluation concept of CT.
5. The fifth activity is data visualization. Students presented their findings into simpler and compact illustrations such as graphs, charts, and tables.

Based on the activities described above, it is clear that CT is flexible and can be a great tool in assisting in STEM learning. In brief, integrating CT in STEM education allows multiple skills to be developed to the students using a real-life problem to be solved in the classroom. There are various approaches to utilize CT in STEM education that can be used to attract students towards learning science, technology, engineering, and mathematics (STEM).



## Conclusion and Suggestion

### Summary and Implications

CT is an active processing in which the students must consider the problem, organize the information they have about the problem, test multiple algorithmic solutions for errors and/or refinement, and also utilize available tools and resources. In short, CT is an active processing that requires systematic manner to formulate and solve problems in a way a computer would do. Similarly, STEM education also works the same way as CT. In order to enhance students' understanding on the subject matter in an integrated STEM classroom, teacher and students can work together to connect STEM subjects in a real-world context.

CT plays significant role in STEM, both in physical skills and mental skills. CT in STEM education focuses on learning by doing, in which the students are required to create a prototype. This learning approach is in line with constructivist view of learning that emphasizes on active learning, thus deepen the students' concentration and understanding on the subject.

### Future Direction and Recommended Research

The combination of CT and science has given a rise to a new field of research, such as bioinformatics. Bioinformatics is a combination between mathematics, statistics, and computer science to study biological molecules and create tools for understanding biological data. This understanding can lead to, for example, new insights into the genetic basis of diseases. In the year 2020, it is said that 50% of jobs in field of STEM will be on computing. With the advancement of technology, complex data and sophisticated mechanism, STEM educators are encouraged to integrate CT in their pedagogy, curricula, and practices because it is clear that CT will become important in the future.

Nowadays with free and easily accessible software in market, it is imperative for teachers to grab this opportunity to obtain the software and using it as a teaching aid in developing CT skills in STEM activities. Furthermore, more collaboration between teachers and STEM experts in creating more CT activities and tools should be done to attract and deepen their interest in STEM fields. Despite the attempts in the past studies as analysed in this research, such approach is not without its own challenges and difficulties. It is hoped that future investigators in STEM discipline are well trained and prepared to face the challenges of complex problem that could not be solved unless CT is practised continuously for many more years to come in line with government's aspired Education 4.0 in this digital era.

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