Chapter

Integrated STEM Education in K-12: Theory Development, Status, and Prospects

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Abstract

In this chapter, we focus on the integrated nature of STEM education in a wide-ranging view. Frist, we briefly interpret reasons why STEM education and synthesize various standpoints of integration in the literature. Then, on the basis of the relevant literature on integrated STEM education, an ideal model is proposed, which include four elements: discipline knowledge, teaching strategies, expectations, and learning system. After that, some analysis and discussion of this ideal model together with all parts of the model are provided. Followed by this ideal model, we have examined the literature on integrated STEM education in action so as to discuss the way to be integrated toward STEM education and enactment of integrated STEM education in practice. Finally, based on this ideal model, a couple of conclusions are summarized and implications are discussed.

Keywords: integrated STEM education, ideal model, K-12 education, curriculum integration, context

1. Introduction

"STEM," an acronym for science, technology, engineering, and mathematics, which was initially proposed by National Science Foundation (NSF) of the USA in the 1990s with the purpose of emphasizing the importance of these four disciplines in the education community and society at large [1, 2]. In a more specific sense, educators have often used it to describe the inherent interconnectedness between the four disciplines and create curricula and pedagogy as well that link them together within one period (e.g., years, semesters or units) or classroom [1]. Since the beginning of the twenty-first century, the notion of STEM has attracted great attention globally and has been regarded as one of the primary foci of educational and curricular policy. However, STEM is not a fixed curriculum. It neither does intend to replace national curriculum frameworks or state curriculum standards, nor does it mean to be a quick fix for education problems [3]. Rather, the STEM education provides an approach to teaching and learning that removes or relieves the traditional barriers of disciplines to foster students' abilities.

2. Redefining the integrated STEM education in K-12

2.1 Why STEM education?

The initial intent of STEM education was to build strengths in science, technology, engineering, and mathematics as a response to the declining number of students undertaking those relevant courses in high school or at university. This intent is underpinned by a perceived decline in STEM teaching quality and a high demand for STEM talents [4]. Thus, one major reason for advocating STEM education in school is to prepare the STEM workforce for the future. Nowadays, the STEM education has actually been evolving from a set of overlapping disciplines into a more integrated and interdisciplinary approach to learning and skill development [5]. This new approach enables and encourages a wider way of integration in STEM education, which includes teaching in a real-world context and combining learning in formal and informal sites. Therefore, it can be concluded that the advocation of STEM education will be beneficial to ameliorate the nation's economy and individuals' comprehensive abilities.

2.2 Various standpoints of integration

People hold broad but different stances on the relationship between STEM integration and education. At the national macro level, policymakers regard STEM integration as a correlation between school education and the development of the social economy. That is, positive STEM education is perceived to contribute to staying economically competitive on a global level. At the individual micro level, educators view STEM integration as an educational approach which might help students become critically literate citizens and procure financially secure employment in their adult lives [1]. Despite different understandings of integration at the macro- and micro-levels, both policymakers and educators point to the interconnection between STEM integration and education. Actually, the literal meaning of integration is combining two or more things together. STEM integration naturally has this meaning; nonetheless, it is not equal to integration of four disciplines as the acronym of this term indicates. Thus, examining the integration on the STEM field should take a holistic and coherent view, that is, not only it comes to educational fields, but it also links to areas like society and economy.

The diversity of viewpoints of STEM integration is mainly due to different emphases on what to integrate into STEM. Some people narrowly defined STEM integration as interdisciplinary integration, with the characteristics of the blurry disciplinary boundary. Others, however, emphasize it on other facets like curriculum integration or workforce integration. Among all the views of STEM integration, the majority of its definitions are limited in curriculum integration, for example, see [6–9]. Until recent years, some scholars like Honey, Pearson, and Schweingruber have proposed a descriptive framework on STEM integration in K-12 education [10]. This framework focuses on discussing STEM integration under the background of K-12 education in a broad view, which involves a range of experiences with some degree of connection, and these experiences can be concluded into four features: goals, outcomes, nature and scope of integration, and implementation [10]. Under this circumstance, STEM integration is equivalent to integrated STEM education. In this chapter, we take this most extensive view of integration to analyze definitions or viewpoints of integrated STEM education in the mainstream literature.

2.3 Elements of integrated STEM education

Based on our literature review on various viewpoints of the integrated STEM education, four outstanding characteristics have been identified and they are counted as constituent elements of the integrated STEM education. In this section, we will discuss these elements one by one.

The first and foremost element is discipline knowledge, which involves scope and intensity. Scope refers to the range of disciplines involved in the integration, whereas intensity is the degree to which the integration has reached. As Drake and Burns pointed out, the most integrated curriculum refers to the alignment of content and context from different disciplines, considering both two main factors: the depth of knowledge within the discipline and the relationship across or beyond disciplines [11]. As it builds on the continuum ranging from within a discipline to across disciplines, it especially cares about the boundary between the disciplines. Two ends of this continuum are segregated disciplines at the beginning of the continuum and integrated disciplines at the end of the continuum. Between them is a gradual mixture of STEM education on the basis of disciplinary knowledge [12]. Some researchers conclude four increasing levels of integration: disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary [13–16]. Similarly, others propose three gradually complexed forms of integration: correlated, shared, and reconstructed, for example, see [17]. In the most advanced integration level, two or more disciplines are merged into real-world problems or ill-structured problems, which help students shape their learning experience. However, most teachers feel that it is the hardest one in class practice because it takes teachers' careful planning and enough time to execute [3]. Due to this consideration, other lower forms of integration in disciplines are also adopted in practice as they are more friendly to contemporary school settings, especially introducing STEM education in the schools' already packed curriculum.

The teaching strategies are the second element to be considered. As we have known, in regular schooling circumstance, the implementation of STEM education relies mostly on how to rearrange the existing curriculum. Teaching strategies may make great contributions to facilitating integrated STEM education in practice. Teaching strategies can be described in many ways. From the epistemological perspective, there are three broad categories: traditional, constructivist, and transformative; while from the perspective of the dominant role, there are two types: teacher-centered and student-centered. Among them, constructivist and transformative approach are common in integrated STEM education, and these teaching strategies are most students centered, including problem-based learning, project-based learning, science fairs, robotics clubs, invention challenges, or gaming workshops. Some of them are mature and widely used in educational fields because they have systematic methods, procedures, and even evaluation criteria. In practice, these teaching strategies can be seen as catalysts or lubricants in integrated STEM education as they have potentials to provide or construct an authentic experience for students to scaffold learning and develop skills or competencies. The project-based learning is one of these types of teaching strategies. It is an approach for students to construct knowledge through teamwork and problem-solving with scientific methods [18]. It has been used for years and involves a wide range of scientific areas where learners concentrate on group learning and presenting various outcomes [19]. Some scholars have attempted to introduce this approach to integrated STEM education to enhance students' attitudes and career aspirations in STEM, and their results are often positive [19–21].

The expectations are the third element, which is usually presented as a series of requirements (like skills and practices) for students to be future democratic citizens and become competent in their adult lives [22, 23]. The element contains several similar terms like literacies, skills, abilities, and competencies. In most cases, literacy is referred to the most fundamental skills or abilities to read and write using paper or technologies such as computers or iPads; skills are transferable knowledge about how, why, and when to apply content knowledge; and the twenty-first century skills are viewed as those that can be transferred or applied in new situation; competencies, however, refer to the blending of content knowledge and related skills, owning the most robust and broad concept [24]. We prefer to focus on skills and competencies as they can be used to describe expectations in large extent: they are more situational, more dependent on learning, and represent the product of training tasks or individual attributes related to the quality of work performance [25]. Moreover, they can be measured by the quality of relevant jobs at work, and an individual's possession of relevant underlying abilities is related to the improvement of a skill [25]. Some frameworks or criteria proposed across the world such as "Key competency," "Core literacy," and "twenty-first century skills" are closely correlated to this element [26]. Although the expectations of STEM education are correlated to these, they are more likely to focus on what competencies those STEM jobs demand. In other words, these frameworks or criteria are developed by experts based on literature review or data collected from employers and educational leaders; whereas the expectations of STEM education tend to find relevant competencies from present data collection of STEM employees [25]. These demands of competencies are desperately needed in workplaces, which prompt schools to cultivate students with these competencies through STEM education.

The learning system is the last element to be integrated. It affords to provide a systematic and appropriate learning environment for STEM education. For decades, efforts to improve STEM education have focused largely on the formal education system, which means that most of STEM-related activities are carried out in school. But integrated STEM education prefers to teach in a more true-to-live learning environment, inevitably, it might be limited by traditional school settings. In recent years, more and more STEM activities have occurred out of school—in organized activities such as after school and summer programs, in institutions such as museums and zoos, from the things students watch or read on television and online, and during interactions with peers, parents, mentors, and role models [27]. The advent of this element was earlier than the popularity of STEM education. It has several origins, for example, cross-setting learning and community of practice. For cross-setting learning, or learning across settings, which means learning by cross-sector collaborations among formal K-12 education, afterschool or summer programs, and/or some type of science-expert organization [28]. For a community of practice, it initially refers to members who have a common interest in a domain or area, or with the goal of gaining knowledge related to a specific field, learn from each other, and develop their personally and professionally [29]. Later on, it has become an integral part of the organization structure [30], which can be used in traditional classrooms, workplaces, or internets. Due to these origins, this kind of learning system is much more comprehensive in that it integrates formal, informal, and after-school education.

Essentially, these four elements make up a wide-ranging view of integrated STEM education, provided that they are put in context-specific landscapes. Many facts show that different contexts could encourage or inhibit these four elements to integrate into a desired STEM education. That is, one successful integrated STEM education means that these four elements interconnect together nimbly according to existing contexts. On the contrary, enacting without focusing on specific contexts may cause failure to STEM integration. In general, these contexts refer to various cultural, physical settings, and social environments. In a specific sense, they can be considered in a small context as well, such as school context, which includes some factors like principals, existing curriculum, and colleagues. The effects of these contexts have inextricably linked to each other but are emphasized differently by stakeholders. Hence, based on a combination of previous analysis and appropriate conjectures, an ideal model of integrated STEM education is suggested in **Figure 1**.

In **Figure 1**, there is a regular tetrahedron with four equal-volume spheres in its four vertexes, which is circumscribed with a big sphere. These four spheres represent four elements, with the lines representing interconnections between them. Moreover, the interspace between circumscribed spheres and the regular tetrahedron is filled with contexts. Within this ideal model, all the components can be adjusted on the condition that they are connected stably.

Contexts are an indispensable matter which contributes to the solid connection of the model. Generally, in a philosophical view, there is no doubt that integrated STEM education should be embedded in historical, political, and economic contexts, as philosophers of science like Thomas Kuhn and Paul Feyerbend reject the objectivity of scientific knowledge and instead favor the ways that science functions within and for societal goals [1]. In this ideal model, the proportion of each element, as well as the connection of these four elements, are situated in social systems and cultural settings to vary degree. At present, the paradigm of global integrated STEM education is mostly dominant by western countries, and their major contexts are in a STEM workforce deficit situation and the competitiveness crisis worldwide. Those countries who have quite different situations from western countries, however, should take a critical but appropriate view to make a suitable integrated STEM education, rather than embracing them without thinking. Apart from this, some specific contexts should be taken into consideration, such as curriculum development mechanism, teaching, and learning traditions. These contexts may overlap but they all have their own focus, and they can affect the cooperation of these four elements to some extent. Discipline knowledge is the most essential and fundamental element in this model, which can be found in almost all the studies on integrated STEM education. It is also a quite stable element that almost free

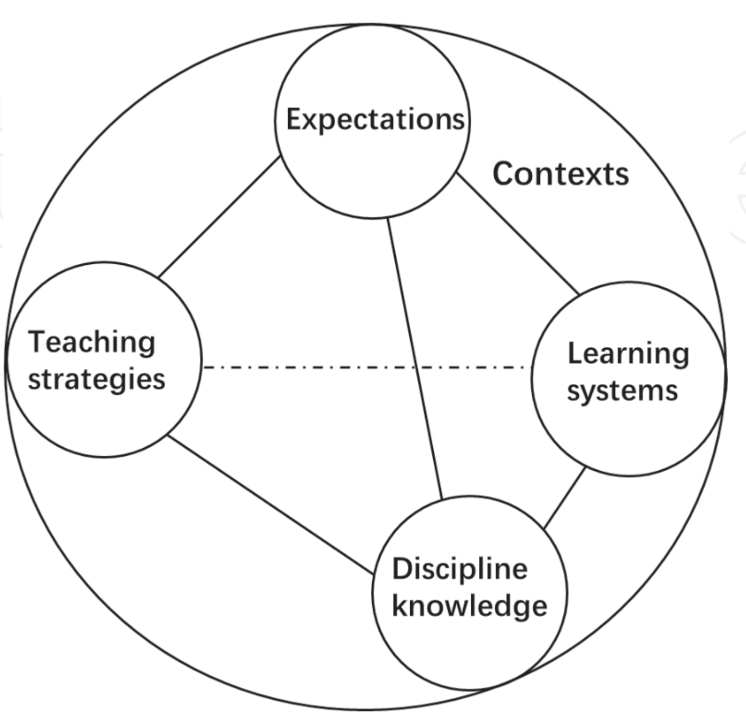

Figure 1.
An ideal model of integrated STEM education.

from the limitation of contexts, except the different emphasis on disciplines that are driven by the needs of the economy and society. At present, the most common view is that STEM disciplines start with science and mathematics with technology and engineering included as an add-on to science. This is reflected in the latest K-12 science curriculum in American [31].

The other three are peripheral supports, playing different but important roles in creating a more integrated STEM education in context-specific landscapes. Teaching strategies, in this model, are mainly used to assist the instruction of discipline knowledge in a given context. Thus, it is natural and necessary to associate discipline knowledge and expectations through context-matched teaching strategies. Besides, the expectations required in K-12 schools should correspond with the needs of future society. In other words, integrated STEM education can provide a possible way to translate social expectations into individuals' real abilities, as long as discipline knowledge and teaching strategies constructing in a good combination. Moreover, the last element, learning systems, is to construct a systematic and appropriate learning environment and to break the limitation of school context in some instances. In short, this ideal model is significant because it can guide the exploration of elements and of the connections between them. Following this ideal model, perspectives on integrated STEM education in action can be further explained and analyzed.

3. Integrated STEM education in action

3.1 How to integrate STEM education in K-12

Like promoting any other educational idea, the way to integrate STEM education in K-12 usually goes through a process from the instructive documents to related curricula products and to the classroom practices. In this process, three steps are in a state of interdependence and proceed from top to bottom, and their sequence cannot be changed or reversed. First, the instructive documents about STEM education in K-12 refer to those curriculum standards, frameworks, or syllabi with latent STEM elements. Since mathematics and science curriculum have two traditional curricula in K-12 contexts for many years while the term "STEM" is not born until the 1980s, most people regard technology and engineering as applied science, providing real-life learning environment. By this approach, students will transform the knowledge and skills acquired in science and mathematics into an engineering product using technology [32]. That is, STEM education expands the extent of science and mathematics curriculum. As a matter of fact, science curriculum has the characteristic of integration in societal and cultural contexts. According to Wei, an integrated science may be characterized by a focus on processes of scientific pupils, or it may be a course structured around topics, themes, or problems that require a multidisciplinary approach [33]. In the latest science education reform in the USA, for example, STEM is advocated as a direction of science education reform in contemporary time [31, 34]. In these two documents, the STEM discipline knowledge is introduced in a transdisciplinary view. Specifically, it is regarded that engineering, technology, and other science-related disciplines as applications of science, which are included in one domain of discipline core ideas. Moreover, it is implied in those documents that mathematics is implicit in all science; models, arguments, and explanations are all based on evidence, and that evidence can be mathematics [31, 34].

Second, when combining transdisciplinary knowledge with other major elements, some integrated STEM education products arise. One typical product is called STEM-focused programs. Since these programs are usually developed for out-of-school organizations, they are free to design and conduct most of the integrated STEM ideas. What they tend to do is to provide integrated STEM education as deep as they can. Such programs like "Engineering is Elementary" (EiE) (https://eie.org/) and "Project Lead the Way" (PLTW) (https://www.pltw.org/) are popular among the STEM education field. They provide teachers and schools with complete STEM-related curricula organized by units or semesters and use project-based learning or engineering design to build an authentic learning environment. Moreover, they also provide opportunities for teachers' professional development and interactions between students and teachers.

Another product is the frameworks about how to conduct integrated STEM education. Usually, these frameworks are user-friendly for teachers in that they are emphasizing that both students' cognitive level (or zone of proximal development) and teachers' knowledge base should align with each other to conduct a successful integrated STEM practice. For instance, Vasquez, Comer, and Villegas have established a two-dimensional integrated STEM framework on the hierarchy of STEM integration levels [35]. In this framework, each level of discipline integration can adjust its depth of knowledge by adapting different instructional approaches with the higher level of STEM integration meaning more rigors and relevance. In all, these frameworks require students and teachers to aware of when and how to apply knowledge and practices from across STEM disciplines [12].

3.2 Enactment of integrated STEM education

In the K-12 environment, despite many theories of integrated STEM education existing in the literature [10, 36–38], ways to operate it are often left to the individual parties [39–41]. That is, individuals have their own perceptions on the integrated STEM education: they themselves interpret, accept, resist or even subvert relevant policies. For this reason, some gaps between expectations and results of integrated STEM education existed. Among these individuals, teachers play an indispensable role in some circumstances, because they are the person who directly conducts integrated STEM instruction in classroom practice, and their perspectives, preparations, and practice on integrated STEM education could result in the divergent between expectations and realities. This is confirmed by Roehrig, Kruse, and Kern who found that the enactment of the prescribed curricula depends strongly on teachers' beliefs [42]. Similarly, teachers' attitudes to and enactment of prescribed curricula are impacted by school context, such as leadership, scheduling, and concurrent reform initiatives. Thibaut et al. have proved that school context is the most strongly related to teachers' attitudes toward teaching integrated STEM [43]. The implementation of integrated STEM education in K-12 requires effective and efficient instructional practice, too [44]. Thibaut et al. proposed a framework with five principles (integration, problem-centered, inquiry-based, design-based, and cooperative learning) and some corresponding instructional practices of integrated STEM education [45]. Obviously, all these instructional practices are linked to teachers' attitudes, and various contexts affect instructional practices and teachers' attitudes.

However, there are multiple barriers to implement an integrated STEM curriculum, and especially, challenges are faced by teachers when they teach integrated STEM. Here, we only focused on three substantial challenges, which are related to pedagogy, curriculum, and school structure fields, respectively [46]. The first challenge is that the pedagogy of teaching integrated STEM requires teachers to change from teacher-led instruction to student-led instruction [47, 48], which might bring much uncertainty in classroom instructions. The second challenge comes from the curriculum field. Teachers may feel difficult to have all the STEM-relevant knowledge in a short time, and they are not willing to learn the concepts or content rapidly [12]. In other words, it is hard for them to get adapted to an integrated STEM approach to teaching and learning. The third challenge is the traditional school structure that limits the depth of integrated STEM education. As we discussed earlier, school context is an influential factor in the ideal integrated STEM education, and its limits are widespread.

Obviously, these barriers and challenges cannot be resolved instantly due to its complexity. Instead, they can be analyzed and explained by our ideal model. In fact, teaching integrated STEM needs a relatively relaxed environment, such as freedom of time and spaces, some supports from principals, colleagues, and parents of students. Any small details in enactment or implementation have a great influence on practices. Except for the expectations, the other three elements together with contexts relate to these three barriers: teachers are lack of discipline knowledge beyong the fields they teach and their teaching strategies do not match with what STEM integration needs; learning system provided is not wide and are constrained by school context. Obviously, as Nadelson and Seifert suggested, there needs to find a way to reconcile the historical structure of schools, curriculum, instruction, and assessment to create a school culture and environment that supports an integrated STEM approach to teaching and learning [12].

4. Conclusions and implications

The significance of this chapter lies in its potential contribution to the existing knowledge system of the integrated STEM education in K-12. First of all, the ideal model we proposed in this chapter is different from many existing models, in that, it is not limited in the integration among discipline knowledge instead it involves four elements, suggesting an integrated STEM education system. Within this system, the interconnection of these elements is flexible and would be efficient when provided with proper contexts. That is to say, each part of the model upholds the others, and in turn, is supported by them. Compared with discipline-based STEM integration discussed in the literature, this model is inclusive. With this model in mind, researchers may realize which part should be improved or revised so as to achieve a more holistic and broad integration. Additionally, for practicing teachers, it might serve as a guiding framework that will assist them to think about how to conduct integrated STEM education in their classroom. Thus, it suggests a possible way to resolve the issues that we have identified earlier and to bridge the gaps between theory and practice in implementing integrated STEM education in K-12. In what follows, we discuss the implications of this chapter and provide some insights on integrated STEM education.

One implication that can be drawn from this chapter is that much more research is needed to understand and analyze the integrated STEM education in specific contexts. For education researchers, this ideal model can be used as a theoretical framework in conducting empirical research in the field of STEM education. For instance, research studies can be done to examine the effectiveness of the implementation of an integrated STEM program. Another suggestion is to do research from practicing teachers' perspectives as they are the most responsible people conducting STEM integration in practice. Based on the understanding of practicing teachers' attitudes, the difficulties, challenges, and barriers they encounter when integrating various domains in practice, some practical and tangible measures might be taken to effectively and efficiently improve their STEM instruction.

Finally, as we mentioned earlier, for the integrated STEM education, it is not the case that more complex the better, but the case that the more suited the better. "Suited" means that those elements match well with the contexts and the proportions of elements are appropriate. More often than not, stakeholders in the field of the integrated STEM education focus on varied aspects. For example, policymakers always stand at the highest point to dominate integrated STEM education but overlook practical issues in the implementation. In most cases, curriculum developers cannot make a balance between ability cultivation and knowledge transmission in curriculum materials they developed, which may mislead teachers' understanding on integrated STEM education. As for practicing teachers, a variety of practical issues may arise as they enact an integrated STEM program or activity in specific situations. Thus, inconsistencies appear when switching among various aspects of the integrated STEM education, which might lead to more barriers and challenges. Therefore, joint and synergic efforts of varied stakeholders are needed to make more effective integrated STEM education on the basis of the model we have proposed.

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