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Toward the Development of Key Competencies: A Conceptual Framework for the STEM Curriculum Design and a Case Study

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National attention has been given to science, technology, engineering, and mathematics (STEM) education, which is well recognized as an effective way to cultivate the key competencies of 21st-century talents. However, current STEM education falls short of the desired results. The fundamental reason is that there has not been a clearly and structurally explained systematic construction and effective implementation of STEM curricula. Accordingly, this article systematically expounds on the construction of the STEM curricula system from four aspects. Specifically, we first proposed the components of the STEM competencies as the goal of STEM education to provide a guiding direction for other parts of the design of the STEM curricula. Then, we elaborated on how to cultivate the STEM competencies from two aspects: the design principles of the STEM curricula content and the implementation strategies of STEM teaching. Finally, we explained how to effectively evaluate to monitor and improve the implementation of the STEM curriculum. In addition to the above mentioned, we then presented a case study of STEM courses constructed under the guidance of "think-based instruction theory" (TBIT) to help readers further understand the nature of the STEM curricula.

Keywords: STEM education 1, curriculum 2, systems framework 3, key competencies 4, think-based instruction theory 5

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INTRODUCTION

The rapid penetration and wide application of the Internet, artificial intelligence technologies, technological products, and big data in daily life have led to an increasingly close relationship between society, science, and technology. Meanwhile, this also brings some new challenges to human life and development (Pleasants et al., 2019), such as socio-cultural diversity, severe global inequality, complex and changing political landscape, and sustainable human development. These complex challenges further put forward the higher request on talents development. Individuals must master interdisciplinary knowledge and abilities within science, technology, engineering, and mathematics fields to adapt to the environment (Taylor, 2016). As a coherent and interdisciplinary approach, STEM education is therefore widely considered a key way to cultivate 21st-century talents who can adapt to and promote social development, as well as has gained a prominent position in education reform in various countries (Saxton et al., 2014). For example, China, the United Kingdom, Germany, South Korea, and Finland have officially included STEM education in government documents.

There is no denying that all education researchers hope to cultivate talents with the key competencies through STEM education, such as communication and collaboration, critical thinking, problem-solving ability, and creativity. Only with these key competencies, students will be able to adapt to the flexible and complex social environment of the future, actively take up social responsibilities, as well as make efforts and contributions to solve critical problems facing by humanity (Saxton et al., 2014).

However, the implementation of STEM education has not reached the expected results in many countries and regions. For example, South Korea strongly advocates STEM education, but many teachers doubt its aims, methodology, and benefits. Chu et al. (2018) explained that, because the STEM curriculum is not grounded in a sound theoretical system, numerous teachers are skeptical of the potential benefit brought by STEM education (Chu et al., 2018). Korkmaz (2018) states that, although Turkey believes STEM education is necessary, they do not have an appropriate curriculum to implement STEM education (Korkmaz, 2018).

In addition, researchers have shown that, although there are many STEM curricula currently available, the lack of consensus on the content and implementation strategies has led to difficulties for schools and teachers to implement STEM curricula (Kelley and Knowles, 2016). At the school level, their difficulty lies in not knowing how to choose high-quality STEM programs. Many current STEM programs simply make students use bits and pieces of knowledge and manipulative skills to achieve a specific goal. Students do not have a deep understanding of interdisciplinary concepts, the nature of scientific practices, as well as their scientific thinking, attitudes, and responsibilities are not developed (Zeidler, 2014). At the teacher level, their difficulties lie in designing appropriate teaching activities and choosing appropriate instructional strategies to integrate STEM interdisciplinary content knowledge, further developing students' STEM key competencies in a holistic manner (Shernoff et al., 2017; Fan et al., 2020).

One reason for the current less-than-expected implementation of STEM education in many countries might be that the systematic construction and effective implementation of STEM curricula have not been clearly and structurally explained (Shernoff et al., 2017). This can lead to difficulties for many frontline educators to truly perceive the value of STEM education and to effectively implement STEM education in the classroom. Therefore, the key question of this article to be addressed is how can a coherent STEM curriculum system be constructed systematically in developing students' key competencies? Specifically, we construct the STEM curriculum system based on the international STEM education experience and our years of research practice, including 1) STEM competencies, as the goals of STEM curriculum, provide direction for content, teaching, and evaluation, as well as play a leading role in the STEM curriculum design; 2) curriculum content and instructional design are the foundational components for achieving the development of students' STEM competencies; 3) evaluation has an important guiding, diagnostic, and pedagogical improvement function for the effective implementation of the STEM curriculum. Next, we briefly introduced a series of the STEM activity curriculum developed by our team with the goal of key competencies development. Finally, a programming-focused STEM curriculum, along with an illustration of its components, is proposed to help educators understand the construction and implementation of STEM curriculums in practice.

THE CONSTRUCT OF STEM COMPETENCIES

STEM competencies are the necessary characters and key abilities to meet the needs of personal and social development, which gradually form in the process of STEM learning. While STEM competencies are widely considered key goals of STEM education (English, 2017), there is no consensus on what STEM competencies should include. Different stakeholders and people in different fields have various priorities. For example, McGunagle and Zizka (2020) through a literature review found that manufacturing employers consider the most essential competency for STEM talent is cooperating with others; secondly, self-motivation; subsequently, communication with others on verbal and written and proactively solving problems (McGunagle and Zizka, 2020). However, in aerospace and defense companies, the ability to solve complex problems is considered the most critical capability, followed by abilities that are flexible to adapt to different environments, collect and analyze data, teamwork, and communication (Marbach-Ad et al., 2019; McGunagle and Zizka, 2020).

It can be seen from the above information that STEM competencies, as a complex framework, should include diverse social backgrounds, such as economic growth, individual development, and related discipline characteristics (Williams, 2017). Nevertheless, most of the existing STEM competencies frameworks only define it from a single perspective, lacking systematization, universality, and coherence (Chamrat et al., 2019). To this end, based on the interview results of different stakeholders (including scientists, science and technology education experts, philosophy of science and technology experts, psychologists, information technology experts, primary and secondary school teachers, etc.), combined with the analysis of different national curriculum standards, we proposed the composition structure and performance of STEM competencies. In concrete terms, interview and review results revealed five common dimensions of STEM competencies: scientific concepts, scientific thinking, inquiry practice, information literacy competencies, and attitudes and accountability (Hu, 2016).

Scientific Concepts

Scientific concepts are thoughts, views, and opinions on the nature and laws of scientific things, which are developed through learning and practice in STEM fields. In different STEM competency frameworks, scientific concepts are considered a basic competent. For example, Tang and Williams (2018) proposed that understanding disciplinary knowledge and its construction process and flexibly applying it to personal problem solving are fundamental components of STEM competencies (Tang and Williams, 2018).

Unlike traditional instruction that focuses on teaching isolated content knowledge, STEM education emphasizes that students can apply interdisciplinary knowledge to solve real-world problems (Shernoff et al., 2017). Therefore, scientific concepts in STEM education fields have various dimensions: mastering the core ideas of specific fields and interdisciplinary knowledge; understanding how scientific concepts, laws, and principles are formed and constructed; forming a basic understanding of the nature of science and technology; and applying concepts, laws, and principles to explain natural phenomena and solve practical problems.

Scientific Thinking

Scientific thinking is a way of understanding the essential properties, inner laws, and interrelationships of objective things (Hu, 2015). It is embedded in different scientific, engineering, and technological practice processes, such as abstract generalization of ideal models based on empirical facts: questioning, criticizing, testing, and modifying different opinions, conclusions, and solutions based on facts and evidence. It can be analyzed and summarized into four dimensions: scientific modeling, reasoning and argumentation, computational thinking, and creative thinking (Chu et al., 2017).

Each kind of scientific thinking ability is composed of thinking content, thinking method, and thinking quality. Among them, thinking quality is the personality characteristic of people's thinking. It reflects the difference in the individuals' thinking level, intelligence, and ability. The quality of thinking mainly includes five characteristics: profoundness, flexibility, criticality, agility, and innovation.

Inquiry Practice

Inquiry practice is not only the main way to form other competencies in the STEM field but also a key competency, mainly including scientific inquiry, engineering practice, digital learning, etc. On the one hand, developing students' understanding of the content knowledge, principles, and the nature of science—what do we know and how do we know it requires students to participate in scientific practices (Duschl and Grandy, 2013). Besides mathematics and computational thinking, collecting and processing information ability, scientific attitudes and accountability, and criteria for engineering design are essential experiences for inquiry practice (Osborne, 2017). Therefore, inquiry practice is of a great value to the cultivation and development of other competencies (Grob et al., 2019).

On the other hand, inquiry practice refers to people's ability to ask questions, design experiments, implement plans, analyze data, communicate results, acquire scientific knowledge, and solve scientific problems (Bell et al., 2010) as well as the ability to conceive, design, operate, implement, verify, and optimize in engineering and technology practice (English et al., 2016). These competencies are the key for them to work in the STEM fields and coordinate their abilities and knowledge to solve problems.

Information Literacy Competencies

Information literacy competencies involve an individual's judgment of information sensitivity and information value, which mainly include information sensitivity, the value judgment of information, information synergism, and information security. The rapid development of information technology has accelerated the production and dissemination of information, reshaped people's concept of time and space for communication, and profoundly affected people's life, work, and study. Different from the past when individuals could only apply their acquired knowledge to solve problems, people can quickly obtain a large amount of information through the Internet at any time in today's world (Bakermans and Ziino Plotke, 2018). Naturally, information and communication technology tools have become the basic tools for learning, working, and problem solving in almost every industry field in the modern society (NEAP, 2018).

However, the abundance of readily available information is false and contradictory. Therefore, it is important to critically evaluate the information obtained, filter the potentially misleading information, further sort out valid information, and apply it to solve problems (Storksdieck, 2016). For this reason, information literacy competencies are thought to be a key component for people to survive in the information society (Gravel et al., 2017). Information literacy provides learners with competencies necessary to consciously acquire, analyze, evaluate, and justify information in an appropriate way, rationally treating the impact of information technology on the human society to improve people's sense of ease and happiness in life in the information society (Wertz et al., 2013).

Attitudes and Accountability

Competency means not only the mastery of knowledge and skills but also mobilizing the attitudes and accountability in the problem-solving process. Therefore, attitude responsibility is widely accepted as an important element of key competencies (Jho et al., 2013; Sadler and Zeidler, 2005). Attitudes and accountability are the right attitudes, values, and social-scientific responsibilities that individuals hold toward science, technology, and engineering in line with the needs of the society (Lee et al., 2012). It is a stable psychological tendency that individuals gradually form during the STEM learning process (Choi et al., 2011).

In dealing with issues like socio-scientific issues, social justice problems, and sustainable development problems, the application of knowledge and ability is influenced and regulated by attitudes and values (OECD, 2019). These issues are always acute, complicated, and with no clear solutions or answers (Wu and Tsai, 2010). Hence, solving such problems involves not only the application of knowledge and skills but also making appropriate, responsible, and effective action decisions based on ethics, compassion toward others, social responsibility, diversity of cultures and values, etc. (Sadler and Zeidler, 2004; Lee et al., 2012).

DESIGN PRINCIPLES OF STEM CURRICULUM CONTENT

The content of the STEM curriculum is a structured system for competency development and works as a director for the teaching. Therefore, it is crucial to clarify how to systematically construct the STEM curriculum content system. Currently, researchers have constructed the STEM curriculum content framework from different perspectives. For instance, Zhou et al. (2020), based on the Australian education context, a design-led STEM curriculum framework was elaborated to guide the implementation of STEM teaching (Zhou et al., 2020). Fan et al. (2020) constructed a STEM curriculum framework which was used to integrate STEM content knowledge into engineering design (Fan et al., 2020). However, the key problem is that the existing framework lacks a systematic articulation of the ground rules and design principles for STEM curriculum content, resulting in inconsistent depth and breadth of designed curriculum content (Bybee, 2013). An uneven level of STEM curriculum content design will further lead to confusion in the implementation of STEM teaching. For this reason, this research first explains how to systematically design STEM curriculum content and then further constructs appropriate STEM teaching strategies on this basis.

How to integrate content knowledge of multiple disciplines and bridge the STEM competency development of students at different age levels is considered the key to STEM curriculum content design (Fan et al., 2020). Therefore, based on the characteristics and objectives of STEM education, combined with the analysis of the existing theoretical framework of STEM curriculum, we explained how to systematically build a framework for STEM curriculum content from two perspectives: cross-disciplinary content knowledge integration around core ideas from a horizontal perspective and content articulation based on learning progression from a vertical perspective.

Integrating Interdisciplinary Curriculum Content Around Core Ideas

As mentioned earlier, enabling students to apply interdisciplinary knowledge, methods, and abilities to solve real-world problems is one of the goals of STEM education (Hoeg and Bencze, 2017; Jiang et al., 2019; Vaval et al., 2019). STEM curricula are therefore interdisciplinary, requiring individuals to integrate concepts, methods, and/or theories from two or more disciplinary sources to solve complex problems involving core ideas (Bautista et al., 2015). Core ideas refer to the core knowledge, principles, and strategies that can link numerous disciplines (Chalmers et al., 2017). Integrating core ideas into STEM curricula helps teachers to connect concepts from a wide range of disciplines in their curriculum design and further helps students to form interdisciplinary knowledge structures or networks of relationships (Bautista et al., 2015). The reasons are as follows.

First, core ideas could provide guidance for selecting STEM curriculum topics and designing interdisciplinary content. Core ideas are key concepts that can link fragmented knowledge points, including two types. The first type is the key organizing concepts that reflect the essence of a discipline, as well as can be widely used to explain and predict a larger range of natural phenomena, such as all earth's place in the universe (Mitchell et al., 2016). The second type is the concepts that have significant explanatory values and exist in multiple sciences or engineering disciplines at the same time, such as the concept of energy exists simultaneously in the fields of physics, chemistry, biology, and geography (NRC, 2012). Therefore, teachers can consider integrating STEM content through core ideas from two different perspectives. On the one hand, a complex real problem is chosen as a learning situation, and then core discipline concepts that can be integrated and applied to solve the problem across multiple disciplines is selected as the STEM curriculum content. On the other hand, a big interdisciplinary idea that exists simultaneously within multiple disciplines is selected as the STEM curriculum content, which is used to construct the context and expand other disciplinary core ideas involved in the context.

Second, core ideas provide students with a boost to transfer knowledge in authentic STEM learning contexts. In terms of the characteristics of the core ideas, the learning of core concepts must be relevant to students' real-life in order to stimulate their interest in learning and to perceive the meaning of what they are learning (NRC, 2012). STEM learning is set in solving complex, real-world problems. Thus, both core ideas and STEM courses similarly start with authentic contexts to facilitate student's transfer of knowledge to problem solving. In addition, existing cognitive science research suggests that the understanding of core ideas contributes to organize and comprehend knowledge more systematically, which can lead to the transfer of knowledge to problem solving more flexibly (Richland et al., 2012).

The Grade Distribution of STEM Contented to Be Determined With the Guidance of Learning Progression

In recent years, learning progression has a more prominent role in science education research (Herrmann-Abell and DeBoer, 2018) and plays a guiding role in the curriculum standards of various countries (Fulmer et al., 2014). For example, the *Next Generation Science Standards* (NGSS, 2013) absorbed the research results of learning progression, constructed their progression matrices for big ideas, interdisciplinary concepts, scientific practice, STSE, and the scientific essence, and constructed the progression diagram for engineering design.

Learning progression, as the hypotheses or models of how students' thinking advances over time (Sikorski, 2019), is closely linked to the core ideas (Hu and Han, 2015). In other words, learning progression is essentially the in-depth and continuous development of the understanding of core ideas (Sikorski, 2019). In addition, educational research has revealed that, only when education is in line with children's thinking development, education can work most effectively (Salinas, 2009). Learning progression, as a series of continuous and interrelated cognitive models, reasonably explains how students' thinking changes gradually over time and close links to the core ideas (Jin et al., 2019).

Therefore, guiding the STEM curriculum content design of different grades following the learning progress can help students construct new understanding based on their original cognition to connect the core ideas learned at different stages. And, cultivating students' understanding of core ideas through learning progression will help students form good knowledge structures, have a deep understanding of scientific concepts, and improve their ability to solve problems.

Specifically, for STEM education, learning progression is, on the one hand, progressive and continuous development of the understanding of core ideas, which is conducive to develop students' understanding of core ideas, content structure, and knowledge evolution paths. Therefore, learning progression can systematically help students learn the connotations of the core ideas and ultimately lay a solid foundation for a comprehensive, systematic, and in-depth understanding of the core ideas. On the other hand, STEM education aims to "grow STEM competencies based on scientific technology and the ability to solve problems in the real world" (Thuneberg et al., 2018). In recent years, research on learning progression has also expanded to include thinking, practical skills, and attitude development. Thereby, learning progression also means the development of other key competencies for STEM education, such as scientific inquiry, scientific thinking, scientific ability, and scientific attitude.

THEORETICAL FRAMEWORK FOR STEM TEACHING

As previously mentioned, in the goals of STEM education, scientific thinking is the core and the basis for linking and leading the development of other competencies (van der Graaf et al., 2019). In the design of STEM curriculum content, it is necessary to follow the law of students' thinking development. STEM teaching, as a key way for students to master the content of STEM curriculums and achieve the training goals of STEM curriculums, should also take thinking as the core. "Thinking-based instruction theory" (TBIT) is a teaching theory that focuses on developing students' thinking and promoting the overall development of STEM competencies. Therefore, we use the thinking-based teaching theory as a guide to design the STEM teaching framework (Hu, 2015).

Based on the latest advances in learning research, in-depth analysis of core competency development pathways, and the systematic research about the influence of teaching behavior on students' development, we proposed TBIT, which focuses on competency development in which thinking is the core, looks at thinking activities in classroom teaching and aims to improve the quality of teaching in the classroom. Specifically, the TBIT includes five basic principles: inspiring motivation, cognitive conflict, self-construction, self-monitoring, and consolidation transfer (Lin and Hu., 2010). Next, we will elaborate on these five principles in conjunction with the TBIT and basic characteristics of STEM education.

Basic Principles of STEM Teaching Based on TBIT

First, inspiring motivation. A key issue faced by STEM education is the students' low retention rate in the STEM field. Student motivation, especially intrinsic motivation such as curiosity and interest, is a fundamental driver of student initiative and persistence in STEM learning (Hallström and Schönborn, 2019; Thuneberg et al., 2018). Therefore, motivation is not only the driving force of STEM teaching but also the key goal of STEM education (Quinn et al., 2020). TBIT also emphasizes that teachers should pay attention to stimulate students' internal learning motivation, mobilize students' enthusiasm for learning, and make them have a strong desire for knowledge so that students maintain positive emotions and attitudes toward STEM learning.

Second, cognitive conflict. One feature of STEM teaching is allowing students to learn actively (Luo et al., 2019). TBIT suggested that the generation of cognitive conflict is the driving force for students' active thinking and active learning, as well as a key engine for changes in their cognitive structures and perceptions. Cognitive conflict refers to the psychological contradiction or conflict that arises when the students' original cognitive structure in the learning process is inconsistent with the real situation (Ross, 1988). Piaget and Dewey pointed out that the generation of cognitive conflict is a necessary condition for students to actively engage in thinking activities (Dewey, 1896). Because the generation of conflicts challenges students' original scientific concepts, it creates an imbalance in students' cognition and further urges students to adjust their thinking to adapt to the new information (Ross, 1988). Therefore, stimulating students' cognitive conflict through situational creation and appropriate question guidance is a key principle of STEM teaching.

Third, self-construction. STEM teaching is a process of self-construction by students under the guidance of teachers, which is in line with constructivist theory. Based on the analysis of constructivist theory and the research results of brain science, TBIT further proposed that self-construction means learners should explain phenomena and solve problems through self-exploration and cooperative communication based on existing knowledge, experience, and cognitive level, so as to realize the meaningful construction of knowledge (Veldman et al., 2020). The characteristic advantages of self-construction are as follows: 1) it is convenient for students to connect the original knowledge and experience with new information, further establishing the connection between the knowledge learned at different stages; 2) autonomous activities can stimulate students' high-level thinking activities and cultivate students' active, autonomous self-management and regulation of learning activities (Zimmerman, 2013; León et al., 2015); 3) cooperation with others can not only stimulate students' thinking and learning motivation but also develop students' cooperation competency, which is also one of the key goals of STEM education (Slavin, 2014; Roberts et al., 2018; Buckley and Trocky, 2019).

Fourth, self-monitoring. The field of cognitive research, as well as new behaviorism, proposed that self-monitoring enables individuals to systematically direct their cognition and behavior toward the achievement of learning goals, influencing motivation, behavior, and volitional control in the learning process (Zimmerman and Schunk, 2011). Flavell and Brown also proposed that metacognitive monitoring is a core component of metacognitive thinking (Flavell, 1979). Based on this, TBIT proposed the pedagogical principle of self-monitoring, which refers to the active planning, checking, reflecting evaluation, feedback, control, and regulation by teachers and students continuously during the teaching process toward the accomplishment of learning objectives. As a complex learning process, STEM requires teachers and students to design and implement learning plans based on learning objectives, to evaluate and reflect on the learning process and results in a timely manner, and to continuously adjust cognitive strategies to complete learning objectives based on feedback results (Zhou et al., 2020; Fan et al., 2020). Therefore, self-monitoring is one of the key principles of STEM teaching.

Fifth, consolidation transfer. The important role of transfer in learning is emphasized in constructivist theory, schema theory, and information processing theory (Pritchard, 2017; Pritchard and Woollard, 2010). For example, the constructivist theory emphasizes that all learning involves transferring prior experience to new contexts. In addition, the development of key competencies also requires students to apply what they have learned in real situations. Based on the basic requirements of developing students' key competencies and the analysis of learning theories, TBIT further proposes the pedagogical principles of consolidation transfer, emphasizing the application of learned knowledge, methods, and attitudes to problem-solving in authentic situations and to other disciplines and domains (Zhuang et al., 2021).

STEM education aims to develop the key competencies that students need to adapt and contribute to the future life of society (Kelley and Knowles, 2016). To this end, STEM education has always emphasized the transfer of core ideas, principles, and skills to solve real-world problems. Therefore, transfer is also a fundamental principle of STEM teaching (Figliano and Mariano, 2015). Combined with TBIT, consolidation transfer in STEM teaching should include two aspects. On the one hand, it means that students learn STEM by integrating and transferring previously learned knowledge, methods, and attitudes to solve complex problems and explore important principles at a deeper level so that they have a deeper understanding of different disciplines or knowledge areas, further constructing new interdisciplinary cognitive structures and improving practical skills in the process. On the other hand, students are expected to transfer and apply the interdisciplinary concepts and methods constructed in STEM learning to other new real-world situations (Figliano and Mariano, 2015).

Six Elements of STEM Teaching

Based on the above five basic principles, we further proposed six basic elements that should be included in STEM teaching: setting up a learning situation, asking questions, independent inquiry, cooperation and communication, summary and reflection, and consolidation transfer (Hu, 2015).

The situation is a clue for students to make connections between old and new knowledge and is necessary for generating cognitive conflict, perceiving and constructing learning meaning, and motivating students to learn. Moreover, STEM education focuses on interdisciplinary learning, while learning situations could provide context to link up the content of various subjects (Martín-Páez et al., 2019). Therefore, teachers must create reasonable situations in STEM teaching.

Asking questions includes allowing students to independently raise questions based on cognitive conflicts and teachers guiding students' deep learning, stimulating students' positive thinking, and maintaining students' learning motivation through the design of a problem chain in the teaching process. The design of the problem should be thinking and challenging, open and exploratory, accurate and appropriate, hierarchical, and organized.

Students test hypotheses and draw conclusions through an independent inquiry and cooperative learning process (Roberts et al., 2018). These two processes are not significantly different in STEM teaching and can be done simultaneously or collaborately after the independent inquiry is completed. In this process, teachers need to help students complete thinking interaction, emotional interaction, and behavioral interaction through a scaffolding structured design and develop the ability to formulate hypotheses, collect and evaluate data, coordinate evidence and theory, communicate and negotiate, etc. (Wang, Han, and Hu, 2015). In addition, the course content should be mapped to the social environment, helping students to establish the connection between tasks, situations, and cultures, and accordingly cultivating the development of students' attitudes and sense of responsibility.

Summarizing and reflecting is a self-monitoring process that focuses on allowing students to evaluate, summarize, and optimize the learning process, and it results through introspection (ElSayary, 2021). This has the benefit of helping students to develop a deep and general understanding of knowledge, methods, skills, and attitudes, refining cognitive strategies and systematically constructing interdisciplinary networks, thus facilitating subsequent application transfer. Given the complexity of STEM learning, teachers should give students ample time in the summary reflection process and provide appropriate scaffolding, such as problem prompts or mind maps.

Consolidation transfer is essentially using a reasonable cognitive structure formed in the mind to understand new knowledge or solve new problems. Through STEM education, students can flexibly apply the knowledge they have constructed, the competencies, the attitudes, and the responsibilities they have developed to solve a variety of relevant problems that will arise. These abilities and awareness can be effectively developed by consolidating the application of transfer (Lu et al., 2015). Both the structural matching theory and the situated theory emphasize that, when the learning situation is the same or similar to the transfer situation, the transfer is more likely to occur (Zhuang et al., 2021). Therefore, the focus of STEM instruction should be on enabling students to construct knowledge in authentic contexts and to transfer learned knowledge, competencies, and attitudes to new and similar authentic contexts.

CONSTRUCTION OF STEM EDUCATION EVALUATION SYSTEM

Teaching and evaluation are two important links in curriculum implementation, and they complement each other. Evaluation not only monitors the effect of teaching but also integrates with the teaching process to promote and ensure the development of students. The effect of evaluation of the curriculum lies in understanding students' performance in the learning process and their problems, identifying the quality level of learning and further providing guidance for the iteration of the curriculum design.

From the perspective of evaluation methods, STEM teaching evaluation includes formative evaluation and summative evaluation (Jeong et al., 2020). STEM teaching is a flexible process, which involves the iterative cycle of activity process and the constant revision of later conclusions. Students' learning content, methods used, and solutions to problems are mostly open. Therefore, formative evaluation adopted in the teaching process is used to provide guidance and continuous feedback for students to monitor the effect of periodic learning and for teachers to modify classroom practice. On the one hand, formative evaluation helps students to monitor their completion of the phased goals in real time, provides feedback for students' learning, and guides students on the next step. On the other hand, it is beneficial to assist teachers to monitor students' learning performance, learning progress, and existing problems in various aspects to facilitate teachers to provide timely guidance to students.

According to the different evaluation subjects, formative evaluation can be further divided into teacher evaluation and student evaluation. The role of teachers is to promote and help students' learning through interaction with students. This requires teachers to constantly understand students' learning conditions through evaluation and timely adjustment in the teaching process and to effectively help students construct their knowledge. Student evaluation, which includes student self-evaluation and student mutual evaluation, refers to students reflecting on the learning process and exchanging mutual evaluation with others (Herro et al., 2017).

At the end of the curriculum, teachers can understand the students' mastery of the overall learning goals through summative evaluation to provide a basis for the effectiveness of the course implementation and further improvement. The index of the summative evaluation mainly revolves around the STEM curriculum goal to constructscientific understanding and application, scientific thinking and practice, scientific attitude, and responsibility.

Students with STEM competencies should be able to connect what they have learned with real life and solve real-world problems (Shernoff et al., 2017). Therefore, summative assessments should enable students to face challenging real-world problems and use the scientific knowledge, skills, and so on they have learned to solve the scientific problems they encounter either independently or in groups.

In the form of assessment, summative assessment can use different assessment methods such as paper-and-pen tests, performance assessment, and computer interactive assessment. The paper-and-pencil test mainly focuses on the steps and procedures of students to solve problems. It generally includes multiple-choice questions, essay questions, and combination questions. Performance evaluation is a supplement to the paper-and-pencil test (Kim and Kim, 2016). Evaluation is based primarily on the level of thinking and practice reflected in the process of solving scientific problems and the results of solving scientific problems. Computer interactive evaluation gives full play to the advantages of modern information technology, such as the realistic presentation of scientific problems through modern multimedia forms, students can operate virtual programs, and so on.

STEM-INTEGRATED ACTIVITY CURRICULUM

"Learn to Think-Learn to Inquire-Learn to Innovate" Curriculum System

Currently, many educators have made great efforts and contributions to the development of STEM curricula. However, most current STEM curricula lack systematic design and do not cover different stages and domains. To address the above issues, our team has developed an integrated STEM activity curriculum system with learning progressions, including three levels: learn to think, learn to inquiry, and learn to innovate. This STEM curriculum takes STEM competencies as the goal, covers different stages, and is guided by thinking-based instruction theory.

"Learn to think" is based on the integration of thinking methods, mainly including 15 basic thinking methods and five comprehensive thinking methods. "Learn to inquiry" integrates curriculum content based on the core ideas and thinking methods and integrates technology, engineering, and mathematics concepts to solve real problems. "Learn to innovate" integrates thinking methods, core ideas, and inquiry practice as well as uses 3D printing, intelligent robots, virtual reality, and other technologies for creative design and product realization. According to the age and cognitive characteristics of different students, the content design of the three courses is also spirally progressive. Next, we will introduce the three curriculums, respectively.

"Learn to think" has a progressive activity system of 10 grades from the preschool class to the eighth grade. The entire course includes 328 activities, which are divided into the basic thinking part and comprehensive thinking part. The materials and resources provided include student books and teacher books. There are 16 books for students: two books for each grade, each with 14–18 activities and four books for teachers, including one for the middle class to the large class in kindergarten, two books for grades 1–6 in elementary school, and one book for grades 7–8. The results of practical research show that the implementation of the "learn to think" curriculum can effectively stimulate students' learning motivation, improve students' self-esteem, and develop students' key competencies such as scientific thinking, academic performance, and peer interaction ability (Hu et al., 2011; Hu et al., 2013; Hu et al., 2016).

"Learn to inquiry" makes a progressive activity system of 6 grades from the first to the sixth grade, including 72 books for students and six books for teachers, with a total of 288 scientific activities. The team also developed electronic resources including lesson plans, lecture videos, teaching reference materials, courseware, experimental videos, imported videos, AR interactive game, micro-exercises, expansion activities, and so on. One of the highlights of the curriculum is that each class hour is provided with a corresponding activity material, in conjunction with other resources, to build an overall solution for primary STEAM learning. This greatly solves the practical problem of "difficulty in organizing experiments and difficulty in finding materials" among frontline teachers.

"Learn to innovate" is a comprehensive activity course that integrates the maker and STEM under the guidance of new technologies, including five technology-supported comprehensive creative activities: intelligent robot, 3D art printing technology, AI and computational thinking programming, intelligent navigation, and virtual reality. Different activities have a distinctive emphasis on key competencies for cultivation. For example, the main purpose of the 3D printing curriculums is to contribute gradually developing spatial concepts to students from grade one to grade three. The Scratch Jr's programming curriculum, from grade one to grade three, adopts the idea of project-based learning (PBL) and is designed to cultivate students' higher-order thinking skills through situational learning. Next, this article will introduce a creative programming curriculum as an example.

Creative Programming Curriculum

Define the Scope of the Curriculum Goal

With the advent of the artificial intelligence era, programming ability becomes more and more important nowadays. In traditional programming courses, students learn only mechanical programming languages. However, computer science is changing rapidly, and the old programming language is bound to be replaced by a new one. Therefore, the goal of programming courses is not to let students master the existing programming language mechanically, but to master the basic knowledge and thinking methods required by programming, as well as stimulate and maintain students' enthusiasm for programming so that students can solve problems in real life through programming.

Based on this, we mainly construct the curriculum goals of students in different stages from four aspects: basic knowledge of programming hardware (scientific concepts), inquiry practice (programming software abilities, inquiry, and problem-solving abilities), scientific thinking involved in programming, and attitude and accountability.

Basic Knowledge of Programming Hardware

As we all know, programming courses for children and adolescents are mainly divided into two categories: software programming and hardware programming. Our creative programming course emphasizes the process of experiencing programming to realize the product, to achieve the understanding of the integrity and visualization of programming logic, and the realization of the goal state of problem solving. Therefore, we pay more attention to the role of hardware in programming courses, understanding the surrounding intelligent environment, understanding the process of the signal input, programming board processing, and data output through hardware principles, and finally building product entities through building robot suite. A specific programming concept involves four fields: programming suite characteristics, programming board, input components, and output components.

Programming Software, Inquiry, and Problem-Solving Abilities

Inquiry practice mainly includes interdisciplinary scientific inquiry abilities and specific technical practice abilities in the programming field. Interdisciplinary scientific inquiry abilities include putting forward problems and hypotheses, exploring product realization principles, exploring software programming logic, function realization, communication, and collaboration, transfer, and expansion. Specific technical practice abilities are as follows:

- can discover the basic functions of different modules of programming software.
- ability to assign values to various simple data.
- can explore the numerical range of variables through serial port printing.
- able to design the sequence structure, judgment structure, and cycle structure program step by step.
- able to implement and define simple functions and use these functions correctly.
- can correctly handle several data of the same type, as well as the comprehensive application of arrays and functions.

Scientific Thinking Involved in Programming

Scientific thinking mainly has two aspects: basic thinking ability and higher-order thinking (critical thinking and creative thinking). The process of collecting and processing information involves basic thinking methods such as observation, classification, comparison, analysis and synthesis, and abstract summary. In the process of programming implementation, it is necessary to clarify the prerequisites and understand the different requirements for products under the same situation, which is an important content in training students' critical thinking. Improving and optimizing the basic ideas provided by the teacher, realizing more novel functions, or making different improvements in details are all manifestations of creative thinking.

Attitude and Accountability

In the process of learning creative programming, students not only learn programming skills, but also maintain and develop their curiosity and enthusiasm for exploring intelligent working principles (algorithmic thinking) through inquiry practice; form a scientific attitude that attaches importance to logic, being willing to explore and cooperate with others; understand the relationship between technology, society, and environment; and improve the sense of responsibility and cooperation.

Design Learning Activities

Primary Course Content

Through the button, touch, pressure, and other actions, obvious sensible physical changes and other single factors control the product sound, light, action single output product function. Teachers should set up simple programming activities, through visual demonstrations, to guide students to understand the structure of programming sentences that are executed in a certain order. For example, "make a little flash stick" can arrange the following activities:

1) Understand the action of "flashing"—on, off, on...
2) Gesture to demonstrate the flicker of different rhythms and understand the role of the "delay" statement in the program.
3) Use a flowchart to demonstrate the process of light flashing: on-delay-off-delay....... Understand the sequence structure, that is, if you need the flash stick to continue blinking, you need to execute this procedure again.
4) Programming realization: the flashing effect.
5) Innovation and expansion: contacting the previous gesture demonstration to achieve different rhythms of flashing, what changes need to be made in the programming statement?

Intermediate Course Content

Through the control of a single factor such as sensible physical change, the function of the combined output of sound, light, and action is realized. In the teaching process, teachers should guide students to discover the characteristics of hardware, put forward reasonable assumptions based on the context, and solve problems through programming. For example, to make a "loud doorbell", teachers can arrange the following activities:

1) Setting situation: Grandpa's hearing is impaired, so he can't hear the knock on the door. Di wants to make a loud doorbell for Grandpa.
2) Inquiry of components: selecting available components; from the name of "capacitive touch" to guess how "capacitive touch" work and how "capacitive touch" is used; exploring the link method of each component.
3) Solving programming problems: make the doorbell sound as soon as it is touched, and understand the triggering mode of doorbell sound.
4) Solving programming problems: Make the doorbell sound upon touch, but with a delayed stop time.
5) Experimental investigation: If "capacitive touch" can work normally, what characteristics (whether it conducts electricity) are required for the object?
6) Innovation and expansion: For people who have no hearing at all, what can be done to improve the doorbell?

Advanced Course Content

By controlling the nonsensible physical change factors, the product can realize the combined output function of sound, light, and action. In the process of students' learning, teachers should pay attention to guide students to observe phenomena, decompose tasks, and integrate thinking activities through visualized teaching activities. For example, making a "door that opens and closes automatically" can schedule the following activities:

1) Contact the existing life experience: observing, analyzing, and comparing the similarities and differences between the automatic door and non-automatic door; understanding "automatic" is mainly reflected in "automatic detection", that is, automatic doors will send out to the motor according to whether there is some "turn" signal.
2) Live scenario simulation. The "automatic door" is understood as a person, divided into the brain (programming board), eyes (sensor), limbs (motor) to demonstrate the working process of the automatic door. Role arrangement: the programming board, sensor, motor, and pedestrian. The pedestrian is shown in several states: entering the sensing area, passing, and after passing. This will help students to understand the "judgment structure" of the programming statements: the sensor needs to determine at any time whether a person is within the sensing area, and the board issues different commands to the "motor" accordingly.
3) Solving programming problems: set the initial state of the door and understand the "position flag" variable.
4) Solving programming problems: By realizing "detect people, doors open normally", understand "if...Perform..." programming statements.
5) Solving programming problems: By realizing "after the person passes, the door closes normally", understand "if...Perform...Otherwise..."programming statements.

CONCLUSION

STEM education is the main trend of education reform in countries all over the world. However, there is a lack of detailed elaboration on how to systematically implement STEM education, which further leads to the product-oriented characteristics of the current STEM education. In order to change this situation and achieve the goal of cultivating the core literacy required by STEM education in the 21st century, this paper systematically introduces the theoretical construction of a STEM curriculum and provides a specific STEM curriculum design case.

To be specific, a systematic STEM course should include contents in four aspects: 1) education goals. As the goal of STEM curriculums, STEM competencies include five dimensions: scientific concepts, scientific thinking, inquiry practice, information literacy competencies, and attitudes and accountability. Among them, scientific concepts are the foundation for other key capabilities. Scientific thinking is the core of the coordinated development of multidimensional ability. Inquiry practice and information ability run through the STEM practice process and are the main ways to form key abilities. Attitudes and accountability reflect the direction of key competencies. Attitude is the mental stability and evaluation tendency, and accountability is the basic moral standard of citizens; 2) curriculum content. The construction of curriculum content includes interdisciplinary integration around big ideas and longitudinal connection under the guidance of learning progression; 3) STEM teaching. Guided by the think-based instruction theory (TBIT), we proposed five basic principles that should be followed in the process of STEM teaching: inspire motivation, cognitive conflict, self-construction, self-monitoring, and reflection and transfer. In addition, based on the five basic principles, we further proposed six basic elements of STEM teaching: setting up a learning situation, asking questions, independent inquiry, cooperation and communication, summary and reflection, and consolidation transfer; 4) the evaluation system mainly includes two approaches: formative evaluation and summative evaluation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WH led the writing, wrote the first draft, created the content ideas and framework, and led the writing and rewriting of the manuscript. XG provided insights, literature search, and collation to the initial draft. Both WH and XG provided initial edits, and contributed to the writing and editing throughout.

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