A Proposed Taxonomy of Teaching Models in STEM Education: Robotics as an Example

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Abstract
Many countries and regions have reached a consensus to promote science, technology, engineering, and mathematics (STEM) education in the past decade. A body of studies have demonstrated that the design and organization of interdisciplinary teaching activities are important for the effective implementation of STEM education. So far, however, little attention has been paid to the taxonomy of teaching models in STEM education. This paper aims to propose a taxonomy based on the dimensions of learning outcomes (i.e., product-oriented and knowledge-oriented) and teaching process (i.e., forward teaching model and reverse teaching model) in STEM education. Through the intersection of the above two dimensions, four teaching models in STEM education have emerged, including project-based learning (PBL), reverse engineering (RE), scientific inquiry (SI), and troubleshooting/debugging (T/D). In addition, four cases are introduced to explain how these four teaching models operate in STEM education. The implications of this work for future research are also discussed. It is promising that the study will be valuable to enrich the current research, and shed light on the theory and practice of STEM education.

Keywords
teaching models, STEM education, robotics courses, taxonomy

Introduction
STEM, a shorthand for Science, Technology, Engineering, and Mathematics, was born in 1990s in the United States. STEM education implies the integration of scientific inquiry, technology, engineering design, and mathematical analysis into a cohesive learning paradigm that incorporates curriculum material, instructional activities, and educational policy (Lai, 2018). Nevertheless, putting them together requires more than just a four-letter word. In recent years, STEM education has received attention from numerous countries and institutions that have been interested in interdisciplinary integration, especially in developing students’ scientific and technological literacy. As an interdisciplinary education, STEM education has the following basic attributes: (1) utilizing real-world issues or problem situations; (2) developing a project-based, problem-oriented, or inquiry-based learning curriculum; (3) having explicit course objectives, content domains, and learning indicators; (4) providing student-centered learning experiences; (5) emphasizing the connection and integration of STEM knowledge; (6) valuing the cultivation of high-level thinking skills such as logical thinking, problem solving, and critical thinking; and (7) highlighting the connection between curriculum and job markets (Fan & Yu, 2016).

Essentially, STEM education is driven by today’s complex policies and economic, social, and environmental issues that require integrated and interdisciplinary solutions (Bryan et al., 2015; English, 2017). In short, it’s a way to connect students’ learning across STEM disciplines (National Research Council [NRC], 2009; STEM Task Force Report, 2014). The integration of STEM disciplines is regarded as complex as the global challenges, requiring a new generation of STEM specialists and cultivating students’ STEM skills (Kelley & Knowles, 2016). In an integrated context, students can approach new problems based on principles previously learned from fields such as science, technology, engineering, and mathematics. Evidence has suggested that STEM education can improve students’ problem-solving skills, creativity, critical thinking, teamwork, and self-confidence (e.g., Altan & Tan, 2021; Honey et al., 2014; Siew et al., 2016). It focuses on guiding students to develop their ability to integrate
interdisciplinary knowledge, stimulating their interest in STEM learning, and assisting them in developing skills for future STEM employment as well as STEM literacy required in the 21st century (Fan & Yu, 2016). As a result, STEM has been widely recognized as a major focus of schooling around the world (Johnson et al., 2013). Having sufficient STEM knowledge, as well as the ability to integrate these knowledge resources to design solutions for emerging problems, has become a key talent valued by the majority of society today (Hoeg & Bencze, 2017).

However, the design of effective teaching models is essential to fully exploit the value of STEM education. Growing interest in STEM education calls for effective teaching models based on the attributes of STEM curriculum. Given this, student-centered approaches based on constructivism are increasingly being considered and adopted (Pedaste et al., 2015; Sayary et al., 2015). In a student-centered approach, students make sense of what they learn in a classroom environment where they are encouraged to develop their reflective and critical thinking skills, as well as their sense of responsibility (Serin, 2018). As a prime example of student-centered approaches, inquiry-based learning is regarded as a pedagogical approach for improving STEM learning in many countries (Bybee et al., 2008). In school science education, inquiry-based learning is a problem-based approach consisting of five pedagogical stages, including engagement, exploration, explanation, elaboration, and evaluation (i.e., BSCS 5E Instructional Model, Bybee et al., 2006). It is worth noting that different STEM disciplines have their own problem-solving processes, such as inquiry-based learning, engineering design, computational thinking, and mathematical modeling (Leung, 2020). Exploring the commonalities and differences in problem solving across STEM disciplines may be the key to expanding the teaching models.

This paper aims to classify the teaching models of STEM education according to the attributes of various STEM disciplines. In this vein, we propose a taxonomy based on the learning outcomes dimension and the teaching process dimension (see Figure 1). In addition, this study also combines the literature on Project-Based Learning (PBL; e.g., Barak & Dori, 2005; Sasson et al., 2018; Usher & Barak, 2018), Reverse Engineering (RE; e.g., Chikofsky & Cross, 1990; López et al., 2019; Rekoff, 1985), Scientific Inquiry (SI; e.g., American Association for the Advancement of Science [AAAS], 1990; Cakir et al., 2011; NRC, 1996), and Troubleshooting/Debugging (TD; e.g., Zhong & Li, 2019; Yerushalmi, 2014) to describe the theory, model and application of these four teaching models in STEM education. The findings can be concluded with implications and suggestions for future research, and provide guidance for STEM education in primary and secondary schools.

It is important to note that the proposed taxonomy is specifically exemplified in the context of robotics courses, which is why “Robotics as an example” has been added to the title. Nowadays, the widespread adoption of educational robots is enabling more students to gain first-hand experience in applying their STEM-related knowledge to address real-world problems (Alimisis et al., 2005). Robotics, with its multi-disciplinary nature, provides a constructive learning environment that is well suited to a better understanding of scientific and nonscientific disciplines (Khanlari, 2013). Empirical evidence has suggested that robotics plays an active role in different scenarios of STEM education (Benitti, 2017). For instance, Demetriou (2011) found that mobile robotics was an effective way to draw students’ attention to STEM topics, even if they did not have a considerable understanding about how robots work. T. Roberts et al. (2018) substantiated that the STEM summer learning experience with robots extended and deepened students’ STEM learning. Smyrnova-Trybulska et al. (2016) supported this view by claiming that classes in robotics will have an impact on the development of mathematical literacy, scientific-technical information, and social competences. Chevalier et al. (2020) concurred, arguing that educational robotics may foster students’ computational
thinking through creative computational problem solving. Accordingly, robots have become an important educational tool in STEM education (Barker, 2012).

**Literature Review**

**Project-Based Learning**

Project-Based Learning (PBL) is a well-structured pedagogical approach that encourages active engagement in authentic investigation of real-life and open-ended problems through cooperation (Barak & Dori, 2005; Sasson et al., 2018; Usher & Barak, 2018). The effects of PBL in improving students' higher-order thinking skills, learning motivation, and engagement have been established in the literature (Kuo et al., 2019; Sasson et al., 2018; Wu & Wu, 2020). PBL has several distinct characteristics that may be identified and utilized in designing a project-based curriculum (Markham et al., 2003). First, PBL relies on the problems designed to drive the curriculum. The problems do not test skills, but contribute to the development of the essential problem-solving skills. Second, the problems are generally open-structured, which means there is no single solution. Third, students are gradually encouraged to address the designed problems and instructors play the role of mentors or facilitators. Fourth, students are provided only with specific instruction on how to deal with the problem, perhaps targeting the necessary knowledge that is critical to identifying alternative solutions to the problems.

The theoretical basis of PBL could trace back to the idea of “learning by doing” proposed by John Dewey in the early 20th century. The concept of project learning is also reflected in constructivism and constructionism. Constructivism (Vygotsky, 1980) explains that individuals construct their knowledge through interactions with the environment, and each individual’s knowledge is constructed uniquely. Individuals learn by constructing new knowledge on top of existing knowledge through surveys, dialog, or activities. Constructionism furthers the notion of individual knowledge construction by positing that individuals learn best when they construct artifacts that can be shared and reflected upon with others, such as plays, poems, pie charts, or toothpick bridges (Harel & Papert, 1991; Kafai & Resnick, 1996). Another important element of constructionism is that artifacts must contain personal meaning to fully engage the individual.

**Reverse Engineering**

Faced with a highly competitive global marketplace, product enterprises are continually seeking for innovative ways to minimize lead times for new product development that fulfill consumer requirements. Reverse engineering (RE) is now recognized as one of the strategies that can bring commercial benefits by shortening product development cycles (Beherens & Levary, 2008). There is no universal definition of RE, as each author defines it within their own research fields. For example, Chikofsky and Cross (1990) defined RE as “the process of analyzing a subject system to identify the system’s components and their interconnections, and to create representations of a system in another form at a higher level of abstraction.” Abella et al. (1994) described RE as “the basic concept of producing a part based on an original or physical model without the use of an engineering drawing.” Eilam (2011) considered that “reverse engineering is the process of extracting the knowledge or design blueprints from anything man-made.” Overall, the essence of RE is to analyze the system, break it down into functional components, and discover how the interactions between the components generate total system functionality. Previous research has indicated that RE can not only help expedite product development (Lee et al., 2003), but also enhance students’ learning motivation (Barr et al., 2000) and learning abilities (e.g., creativity, understanding, hands-on skills, and insight).

The term “reverse engineering” originates from hardware analysis where it’s common to decipher a design from a finished product (Chikofsky & Cross, 1990). A RE model is described that is based on the premise that a complex hardware system can be characterized as a hierarchical structure (Rekoff, 1985). This model was first born in World War II and played an important role in the development of aircraft, tanks, and other military equipment. RE is now widely employed in numerous applications (e.g., manufacturing, industrial design, and jewelry design, etc.) to improve products. The educational application of RE first appeared in the late twentieth century. Through RE, students acquire the knowledge required to develop their product, computer program, or chemical plant, and proceed to the upper levels of Bloom’s taxonomy: design, implementation, and evaluation (López et al., 2019). Similar to reverse reasoning, RE is a process of addressing problems by employing reverse thinking. Guided by social methodology, it applies modern design theories, methods, and techniques with professionals’ expertise, knowledge, and thinking to dissect, analyze, reconstruct, and recreate existing products. In the field of engineering design, it has a unique connotation which is also regarded as the design of the design.

**Scientific Inquiry**

Inquiry in science education is one of the few overarching themes that cut across school curricula all over the world (Abd-El-Khalick et al., 2004). The incorporation of scientific inquiry (SI) in the K-12 school curriculum has been regarded as one of the four core objectives of science instruction for a long time (Cakir et al., 2011). Helping students develop informed views about SI is a significant part of scientific literacy (D. A. Roberts, 2008). In the early 1900s, Armstrong and Dewey began to advocate the use of
SI for teaching. In the late 1980s and 1990s, SI was emphasized again as a key component in curriculum reform efforts, such as the National Science Education Standards (NRC, 1996) and Science for All Americans (AAAS, 1990). The NRC defines SI in the following terms: “Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. The inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world.” (NRC, 1996). Since the definition of the NRC has been widely cited and acknowledged, renewed recognition has been provided that the enhancement and application of SI is one of the essential elements of science education.

Authentic SI is characterized by: development of individual and cultural knowledge; contextualized scientific knowledge; progress toward high-order problem solving; and social interaction for scientific objectives (Hanauer et al., 2009). SI is injected by concrete theoretical knowledge, which is contextualized in very specific ways (Hodson, 1996). Meaningful SI is typically contextualized within a specific and established knowledge structure rather than the abstract application of procedural knowledge (Hanauer et al., 2009). In the inquiry-based learning model, students are encouraged to ask questions and conduct research on topics of interest to make their discoveries, rather than developing products or artifacts with practical applications. Besides, science is not accomplished by oneself, but by the community, so students are expected to address inquiry-based problems, construct knowledge, and engage in shared efforts (Cakir et al., 2011; Dillenbourg, 1999).

Troubleshooting/Debugging

American educational psychologist Edward Lee Thorndike considers that learning is an iterative process of “try-error-try again.” Errors have an “invisible” positive effect as they can alert students to where there is a gap, encourage students to think and explore new ways to address problems (Frese et al., 1991). Although teachers and researchers have long recognized the importance of analyzing students’ errors, they have not really used errors as a means of teaching to help students learn. Until 1994, Borasi (1994) initially utilized error as a springboard to explore how students can use the potential of the error to prompt and support mathematical inquiry. The results showed that the students’ reasoning ability, mathematical thinking, and problem-solving ability have all been improved. In addition, VanLehn (1999) pointed out that errors can impede learners in the early stages of developing complicated cognitive skills, but they also stimulate students to ponder and develop a better comprehension of their knowledge. With the popularity of the idea of “using errors to help students learn,” troubleshooting/debugging (T/D) has gradually gained attention in the field of education. As a special form of problem-solving, T/D is a process that attempts to locate the causes for the malfunction in a given system and then repair or replace the faulty component to make the system return to normal (Jonassen & Hung, 2006; Kester et al., 2006; Yerushalmi, 2014). T/D is popular in a wide variety of professional contexts, such as diagnosing illnesses, debugging computer programs, and repairing electric circuits (Van De Bogart et al., 2017). Due to the interdisciplinary nature of STEM education, students will inevitably encounter complex, unpredictable, and open-ended troubleshooting problems. The experiences of T/D can effectively promote students’ understanding of concepts, develop students’ reasoning ability, problem-solving ability, and learning performance (Booth et al., 2013; Borasi, 1994). Therefore, T/D is considered as one of the most critical problem-solving skills required of citizens today (Labe, 2015).

Taxonomy on Teaching Models in STEM Education

Cultivating students’ creativity is a priority in 21st century schooling. Creativity is considered as the ability to generate new and valuable ideas (i.e., poems, recipes, and scientific theories) or artifacts (Boden, 2004), which represents a learner’s high-order thinking skills sets. STEM education is one of the important means to develop creativity (Altan & Tan, 2021; Capraro & Han, 2014; Henriksen, 2014), and its learning activities can be classified in the form of final learning outcomes. For instance, it could be formulating a mathematical model, or forming of a theoretical design, or constructing an artifact. The form of the final product depends on the activities’ objective (Sokolowski, 2018). According to students’ learning outcomes in STEM education, we can obtain two different orientations of learning objectives: product-oriented (i.e., to form physical results) and knowledge-oriented (i.e., to acquire multiple knowledge). Product-oriented STEM education emphasizes that students use computers and other technical tools (e.g., open-source software and hardware) to generate materialized learning outcomes. Indeed, STEM education with this orientation is extremely similar to Maker Education. In contrast, knowledge-oriented STEM education is equivalent to a platform of scientific inquiry, which aims to acquire knowledge (e.g., survey report, solution, etc.) in the process of scientific inquiry.

Engineering is the discipline that addresses problems by designing processes or products integrating science and mathematical knowledge (Brophy et al., 2008). Engineering design is increasingly recognized as a fundamental strategy for all integrated STEM courses (Daugherty & Carter, 2018). Forward engineering and reverse engineering are two types of engineering design (Beherens & Levary, 2008) commonly used in engineering education (Luna et al., 2011). Universities are currently using forward engineering and reverse engineering to enhance the skills and capabilities of engineers.
Reverse engineering requires students to extract information from an off-the-shelf product (Curtis et al., 2011) to reveal its design solutions and develop an improved product (Verner & Betzer, 2001). In this process, students can learn about the functions of the products, as well as the relationships between the components (López et al., 2019). Forward engineering was developed to better understand mathematics and science under the concept of STEM (Yu, 2016). Unlike reverse engineering, it is a conventional process of moving from high-level abstraction and conceptual designs to physical implementation (Rekoff, 1985). Both reverse engineering and forward engineering can help students address problems in STEM education. In this way, according to the direction of the teaching process, we can get two different implementation models of STEM education, namely, forward teaching model and reverse teaching model.

The framework presented here (see Figure 1) shows that through the intersection of the above two dimensions, four teaching models in STEM education have emerged, including project-based learning (PBL), reverse engineering (RE), scientific inquiry (SI), and troubleshooting/debugging (T/D). PBL and SI share similar pedagogical logic, where students learn through problem analysis, solution design, and information discovery or artifact creation (Sahin, 2013), that is, forward teaching model. RE and T/D use a reverse teaching approach where students start with an existing artifact or a semi-finished product, use or test it, trace its production method, and then restore or redesign it (Zhong et al., 2021; Zhong & Si, 2021). Meanwhile, product-oriented PBL and RE require students to make artifacts directly, while knowledge-oriented SI and T/D focus on developing students’ ability to analyze problems and explore knowledge in the real world. The details of this taxonomy are as follows.

**Model of Project-Based Learning in STEM Education**

With the increased emphasis on the E (engineering) in STEM, project-based design is increasingly being integrated into STEM education and is defined as “a well-defined outcome with an ill-defined task” (Capraro & Slough, 2013). In project-based learning, tasks are often complex and open-ended, involving a series of activities such as design, problem-solving, decision-making, or investigation (Jones et al., 1997; Thomas, 1999). Teachers are facilitators of learning activities, and students are responsible for self-directed learning (Savery, 2006). As for classroom design, project-based learning does not advocate the use of rigid lessons to guide learners along specific paths to learning outcomes or objectives. It emphasizes the integration of real-world problems into an interdisciplinary project, allowing for in-depth exploration of worthwhile topics (Helm & Katz, 2016). In this context, students develop projects through an iterative process of design, production, and evaluation. Previous studies have found that project-based learning enables students to have more autonomy over what they are learning, which is more conducive to maintaining interest and motivating students to take more responsibility for their learning (Tassinari, 1996).

As mentioned above, project-based learning in STEM education is grounded in engineering design, where students apply their knowledge of science, technology, and mathematics to address meaningful real-world problems (Capraro & Slough, 2013). Engineering design can be defined as a set of procedures used by engineering teams to help them solve problems (Daugherty & Carter, 2018). A large body of literature has attempted to describe the model of engineering design process. Some illustrated it as a loop, circle, or spiral of procedures that, if followed loosely, would lead to a successful conclusion (Dugger & Gilberti, 2000). An engineering design process typically includes the following steps or procedures: conducting research and gathering information, developing a rough idea, proposing potential solutions, creating representative models, creating prototypes, testing solutions, and communicating results (Daugherty & Carter, 2018). Combined with the above analysis, we proposed a model (see Figure 2) that divides the implementation process of project-based learning into five stages: demand analysis, analysis of alternatives, detailed solution analysis, implementation and testing, and project packaging and sharing. This cycle reflects the general process from product design to product production, and finally to consumption and use. However, product development is usually not a smooth process. Students need to design and improve solutions through iterative design.

**Model of Reverse Engineering in STEM Education**

Rekoff (1985) introduced a five-step reverse engineering procedure which has been successfully applied to a complete major weapon system: (1) assimilate existing data, (2) identify elements, (3) disassemble, (4) analyze, test, and dimension, and (5) complete documentation. Otto and Wood (1998) proposed a new reverse engineering and redesign methodology, which focused on the process steps required to understand and represent a current product. It consists of three stages: (1) trial and experience, (2) modeling and analysis, and (3) redesign. Based on this reverse-engineering approach, Wood et al. (2001) launched and tested their new courses at the University of Texas, MIT, and the United States Air Force Academy. The results suggested that reverse engineering is an effective way to teach design to students while utilizing “hands-on” projects.

According to the teaching objectives and learning results of reverse engineering in STEM education, researchers divide the reverse engineering teaching model into two types: recovery experiments and reconstruction experiments (see Figure 3). Recovery experiments aim to recreate design abstractions from source code, existing design documentation, personal experience, and experts’ knowledge.
about the problem or application, and reproduce all the information required for a person to fully understand a program (Biggerstaff, 1989). A reconstruction experiment is the transition from one representation to another that includes altering the subject system into a new form while retaining its external behavior (Canfora & Di Penta, 2007; Chikofsky & Cross, 1990). In robotics courses, recovery experiments mainly focus on the understanding of basic knowledge relating to the concept, structure, and function of robotics and are designed to restore a complete product. Reconstruction experiments refer to the addition of innovative elements based on the understanding of basic knowledge. The goal of this kind of experiment is no longer limited to restoring existing products, but to creating innovative products.

These two types of experiments can be further subdivided (Zhong et al., 2021). For recovery experiments, according to the directional principle of task classification, it can be divided into deconstructive restoration and trouble-shooting recovery (Zhong et al., 2016). Deconstructive restoration means that teachers provide complete products when conducting recovery experiments. Trouble-shooting recovery refers to the provision of faulty products when conducting recovery experiments. For reconstruction experiments, according to difficulty level and innovation degree of the reconstructed works, it can be distinguished as add/reduce elements suitable for near transfer and structural innovation suitable for far transfer. The former refers to the modification of the elements or parameters of the product (i.e., add/reduce elements). This type of reconstruction experiment can contribute to a simple transformation based on the original product. The latter requires students to have a certain interdisciplinary integration ability to restructure/redesign existing products (i.e., structural innovation).
Model of Scientific Inquiry in STEM Education

Inquiry-based learning is an approach that engages students to explore their questions and interests by proposing and refining questions, making predictions, designing plans, gathering and analyzing data, drawing conclusions, proposing new questions, and producing artifacts (Blumenfeld et al., 1991). In order to promote higher-level practical teaching in STEM education, several studies proposed the use of inquiry-based teaching to encourage technological exploration and strengthen the effect of STEM education (Barry, 2014; Chang & Yang, 2014; Cheng et al., 2016). Barry (2014) and Chang and Yang (2014) designed an inquiry-based 6E teaching model with the following procedures: (1) engaging, (2) exploring, (3) explaining, (4) engineering (elaborating), (5) enriching, and (6) evaluating. Bell et al. (2010) identified nine main procedures of scientific inquiry, supported by different computer environments: orienting and asking questions; hypothesis generation; planning; investigation; analysis and interpretation; modeling and exploration; assessment and conclusion; communication; and prediction. Leung (2019) explored a blended pedagogy that links mathematics and science in STEM disciplines through teaching loops that incorporate elements of inquiry-based learning.

Robots can provide immediate visual and tactile feedback to improve the attractiveness of students’ inquiry learning. Using robots for scientific inquiry learning has the potential to become a new educational trend (Altin & Pedaste, 2013). When exploring the impact of robotics on students’ STEM learning, Barker (2012) found that students’ self-efficacy and problem-solving skills were greatly improved. Studies also indicated that robotics education has the potential to improve students’ creativity, critical thinking ability, decision-making ability, and teamwork ability, which are integral components of scientific inquiry activities (Nugent et al., 2010). Therefore, using robots as a tool or platform for scientific inquiry is one of the important development paths for STEM education. The scientific inquiry teaching model suitable for STEM education presented here consists of four stages: tool design, element design, contextual design, and evaluation design (see Figure 4).

**Tool design.** Collecting data is a complicated but important part in the process of scientific inquiry. The continuous improvement of sensors has resulted in a more convenient and efficient way of data collection. Composed of various sensors, robots now have a more powerful ability to automatically acquire and collect data, which makes it a powerful tool for scientific inquiry activities.

**Element design.** Bybee et al. (2008) proposed five stages of scientific inquiry: proposing problems, establishing hypotheses, designing research plans, testing hypotheses, and expressing or communicating results. We refined this process based on empirical experience to: (1) raise a question, (2) develop a hypothesis, (3) make plans and design experiments, (4) conduct experiments and collect data, (5) analyze the data and draw conclusions, and (6) evaluation and reflection.

Asking questions is the first step in scientific inquiry. The process of scientific inquiry will revolve around the inquiry questions. The inquiry can proceed in an orderly manner only if the questions are clear and specific. The hypothesis must be verifiable. It is not a casual random guess, but an interpretation of the possibilities of the explored questions based on the learner’s existing experience. Planning and designing experiments is the key step that directly affect whether the inquiry process is scientific or not. The experiments directly determine the correctness of scientific inquiry results. Data processing and analysis is designed to provide students with a deep understanding of the inquiry questions. Finally, students should present their research findings and allow others to express different opinions or doubts about their inquiry process and outcomes. Afterwards, students should seriously consider the opinions of others and improve their inquiry plans.

**Contextual design.** In scientific inquiry activities, the context designed by teachers should be both real and instructive. Careful contextual design is helpful for students to identify problems in the real world, formulate hypotheses, and determine the solutions to the problems.

**Evaluation design.** Our framework will evaluate learners’ performance at each stage based on the general process of scientific inquiry. In the following section, the authors will share a case study of scientific inquiry in STEM education.

Model of Troubleshooting/Debugging in STEM Education

Troubleshooting/debugging is a type of problem-solving technique commonly employed in the fields of engineering and computer science. It encompasses four steps: (1) recognizing that something is not working or not meeting the stated goal; (2) deciding to either keep their original goal or switch to an appropriate alternative; (3) generating a hypothesis as to the cause of the problem; and (4) finally, attempting to solve the problem (Bers et al., 2014). Combining the error correction process designed by McLaren et al. (2012) and the characteristics of STEM education, Zhong and Si (2021) divide the process of error correction teaching into the following steps (see Figure 5): (1) the teacher designs learning tasks and wrong solutions based on the task requirements, (2) students learn new knowledge under the guidance of teachers, (3) the teacher presents the student with a learning task and prompts the student to correct the error, (4) students identify, analyze errors in learning tasks and try to debug errors, and (5) students explain the cause of the error and try to correct the error under the guidance of the teacher.
Cases and Discussion

Case of Project-Based Learning in STEM Education

As an interdisciplinary education, robotics easily lends itself to project-based learning. Robotics has the potential to put people from different backgrounds and fields together to collaborate on a single project (Kitts & Quinn, 2004). In this section, we present a case study of robotics education applying project-based learning. The project introduced the working principle of ultrasonic sensors and allowed students to use ultrasonic sensors to realize functions such as ranging and obstacle avoidance. The participants were sixth grade students. The robot kit used in this project was a blue smart car produced by CFunWorld, and the programing software used is AS-Block, which is evolved from Scratch, a block-based visual programing language. Each lesson lasted for 40 minutes. The learning task is to use AS-Block and the blue smart car to achieve ultrasonic ranging in the form of group cooperation. Students are required to fill in the learning record sheet, including four parts: design intent, production process, sketching and program flow chart, and summary. In the following, we will introduce the process of this case study in detail according to the five stages of project-based learning.

Demand analysis. In this step, teachers first explained to the students what is a smart detection car, and the application of obstacle avoidance in real life. Then, students began to analyze the requirements, and describe the design intent and function of the smart detection car in the learning record sheet.

Analysis of alternatives. Students worked in groups to design the implementation plan of the smart detection car. They first learned the function, structure, principle, and
usage of ultrasonic sensors; then explored how the ultrasonic sensor measures distance, and finally discussed how to use ultrasonic sensors to avoid obstacle. After completing the principle study, students worked together as a unit to design the alternatives of smart detection car. The students jointly agreed on the production sequence to ensure that the project is organized.

**Detailed solution analysis.** Students began to design and draw the structural sketch and the program flow chart of the product. During this period, the teacher did not directly tell the students what to do, but only gave hints or help. After completing the design, the teacher checked it to ensure feasibility.

**Implementation and testing.** The teacher distributed the smart car parts, ultrasonic sensors, screws, screwdrivers, and connecting wires to the students in advance. The student assembled the smart car according to the product design sketch. Wrote the program according to the program flow chart and uploaded it to the smart car. Next, the students tested whether the car successfully avoided obstacles. Various problems may arise in this process. The students improved their solutions through iterative design. The teacher was always ready to give guidance. This process helped develop students’ iterative awareness and problem-solving skills.

**Project packaging and sharing.** In the final step, the students compared and summarized the products to check whether the smart detection car had reached the expected goals. Successful students were encouraged, and those who did not complete the smart detection car was also encouraged by the teacher to analyze the reasons. Finally, the teacher evaluated the performance of all students in the project-based learning and made suggestions for improvement on the problems that emerged.

**Case of Reverse Engineering in STEM Education**

Reconstruction experiment is an important branch of reverse engineering teaching model in STEM education. In robotics courses, structural innovation refers to the process of student’s exploration of robot decomposition and structural reconstruction under the guidance of teachers. It includes three steps: disassembly, analysis, and redesign. The following describes a “multi-functional car” project. It guides students to the innovative design of the existing robot through four stages: trial and perception, decomposition and observation, structural reconstruction and testing, and evaluation and summarization. The participants were sixth grade students. The robot kit used was a blue smart car produced by CFunWorld, and the programing software was AS-Block.

**Trial and perception.** The teacher distributed a fully installed car to each group. Students worked in groups to test the car and perceive the composition and function of the car. Each group was asked to record the main functions and features of the car in a specific table.

**Decomposition and observation.** First, students disassembled the parts of the car, understood the structure, and recorded the disassembly sequence, part names, and connection methods in the table. Second, the students guessed and verified the running program uploaded by the car based on the product trial experience. The teacher did not provide a ready-made program for students. Students recorded the program decomposition process and draw the program flow chart. Here is a set of records that disassemble the hardware and program (see Figure 6).

**Rehabilitation and structural reconstruction.** Students first restored the function of the car based on the disassembly results. Students then worked in groups to redesign the
function or structure of the car. This task helped to cultivate students’ creativity and logical thinking. Before starting the redesign, the teacher introduced the meaning of the multi-function to the students. Students were asked to propose functions to be modified or added based on the existing products, and to describe the product structure to be modified according to the changes in functions. The teacher were only responsible for supervising students and did not directly prompt or guide students. After completing the “redesign,” the teacher examined the students’ plans and helped them analyze the feasibility of the plans. Then, students designed the product structure sketches and program flow charts.

Testing and evaluation. In this step, the students began to test the function of the car. When they encountered difficulties in testing the car, the teacher gave guidance rather than ready-made solutions. It is worth noting that during the test, students were allowed to adjust the project according to the actual situation. After completing the car test, students self-assessed whether they have met their expectations. This process helped students reflect on design intent and review problems and solutions encountered during the redesign process. Finally, the teacher reviewed the student’s performance throughout the project. Students who successfully completed the redesign were encouraged by the teacher. For students who did not complete the redesign, the teacher made suggestions for improvement based on existing difficulties and helped students reflect on the reasons.

Case of Scientific Inquiry in STEM Education

In this case study, students explored the cycle of a simple pendulum using Arduino open-source hardware (i.e., infrared digital obstacle avoidance sensor) to explore simple pendulum cycles. Compared with traditional physics experiments, this project helped students learn the basic knowledge and skills of robotics, cultivate students’ scientific inquiry ability and improved their learning attitude. The participants were senior high school students. The robotic kit used in this case includes: Romeo controller, infrared digital obstacle avoidance sensor, USB cable, and 3P cable. The programming software was Mixly. It uses Arduino IDE as compiler and supports all Arduino boards. The process of scientific inquiry is described as follows:

(a) Leading the question: How long does it take to swing the pendulum back and forth? Students gathered relevant information on this question and discussed it in groups. The teacher showed the students a simple pendulum experiment diagram commonly used in physics class, and explained the concept of cycle and the working principle of the pendulum. Then, the
teacher showed the traditional pendulum experiment device to guide students to think about the possible problems in the experiment. The students were asked another question: Can we use Arduino open-source hardware to make experimental equipment to solve the problems?

(b) Make inquiry plans: The teacher introduced a new sensor to the student: the infrared digital obstacle avoidance sensor. Students developed research plans and designed experiments in groups. Each group designated a member to report on the group’s inquiry plan. All research plans were scored by other groups. Finally, the teacher summarized the students’ performance.

(c) Conduct the experiment: Students followed the established experimental procedures and used Arduino to build a device to collect experimental data (see Figure 7). Finally, all groups draw their own experimental conclusions and used statistics data to validate or falsify their hypotheses.

(d) Evaluation and communication: Students reported the experimental data and conclusions obtained by the group, and evaluated the inquiry experiments of other groups.

**Case of Troubleshooting/Debugging in STEM Education**

The purpose of this case study is to design error correction tasks to explore the role of troubleshooting/debugging teaching model in STEM education. Designing error correction tasks can help teachers understand the mistakes that students often encounter in STEM education, which can be grouped into four types: communication errors, control errors, sensing errors, and system errors (Zhong & Li, 2019). In this case study, students designed and made robots with specific functions through modular programing. Therefore, the error correction tasks set by the teacher were mainly control errors, and a small part involved communication errors, sensing errors, and system errors. In order to comprehensively evaluate the teaching effect of the troubleshooting/debugging teaching model, a control class using traditional problem-solving teaching method was also set up in this case study. Students in the control class learned and mastered robotics knowledge and skills by completing routine tasks rather than error correction tasks (Yerushalmi, 2014). The evaluation of teaching effects mainly involved students’ mastery of robotics knowledge and programming skills, problem-solving ability, learning attitude, and learning immersion.

In this case, students used an entry-level robot kit for STEM education, that is, the mBot robot car. It can help students understand robotic mechanical and electronic parts. The building block programing software mBlock is used in conjunction with the mBot car. Both mBot and mBlock are products launched by MakeBlock for entry-level learners in STEM education.

During the experiment, the two classes adopted different teaching methods for experimental intervention. Students in experimental class used the troubleshooting/debugging teaching model to learn robotics courses and students in control class used a conventional problem-solving teaching model. The teaching process was divided into four steps: (1) the teacher designed and presented the learning task, (2) the teacher prompted the student to analyze the specific problems that need to be solved, (3) the student proposed the solution and discussed the sharing, and (4) the teacher provided feedback and guidance based on actual conditions. The teaching experiment lasted for 6 weeks and 2 hours per week. After the experiment, the results revealed that there was no significant difference in the basic knowledge and programming skills of robotics mastered by the two classes. However, students’ problem-solving ability and self-confidence in experimental class were better than those in control class. In terms of enjoyment and emotional immersion, the two classes showed opposite results. Students in experimental class experienced better enjoyment and emotional immersion than those in control class. There were no significant differences in values, behavioral immersion, and cognitive immersion between the two teaching models. Despite this, for STEM education (especially robotics education), the troubleshooting/debugging teaching model showed important educational potential to a certain extent.

**Conclusions and Future Directions**

A body of studies indicated that STEM education has great value in reinvigorating students’ desires to understand the
Comparison of Four Teaching Models.

| Teaching goal | Learning to invent with a robot | Learning to imitate with robot | Learning to inquire with robot | Learning to initiate with robot |
|---------------|--------------------------------|-------------------------------|-------------------------------|--------------------------------|
| Learning task | Project development            | Product recovery and redesign | Problem exploration           | Problem debugging              |
| Learning outcomes | Design innovative product     | Redesign innovative product  | Solve scientific problems     | Solve pre-set problems         |

One thing we would like to emphasize again is that the teaching objectives, learning tasks, and learning outcomes varied with different teaching models. For example, the learning outcomes of both PBL and RE are product-oriented. However, the PBL teaching model is designed to require students to design innovative products in project learning. The purpose of the RE teaching model is to learn how to imitate and redesign off-the-shelf products. Likewise, the learning outcomes of both SI and T/D are knowledge-oriented. But the goal of SI is that students learn how to solve scientific problems through a series of inquiry procedures. T/D, on the other hand, focuses on guiding students to solve predetermined problems through debugging and error correction. The differences and connections of the four teaching models in STEM education are presented below (see Table 1).

One thing we would like to emphasize again is that the application scope of these four teaching models in STEM education is different. Each model has its own characteristics, so no one model is necessarily better than the other. Whether these four teaching models can achieve good teaching effects in STEM education depends largely on teachers’ flexible design and regulation of classroom activities. Therefore, teachers should comprehensively evaluate each teaching model and make wise choices based on the content of the STEM course, the ability level of students, the arrangement of teaching progress. Furthermore, teachers also need to consider other factors that may affect the teaching effectiveness, such as time and classroom layout. For example, choosing troubleshooting/debugging or reverse engineering will take much more time than PBL for the same teaching content. PBL is more suitable for the pursuit of efficiency. But if teachers want students to spend more time experiencing and exploring, the other three teaching models may be a better fit. To this extent, it is a challenge for teachers to appropriately design and flexibly apply these teaching models in STEM education.

It is also worth noting that the reverse engineering teaching model and the troubleshooting/debugging teaching model are rarely employed in current STEM education. If practitioners are still troubled by the vague learning objectives and single learning models of STEM education, it may be a good choice to try these two cutting-edge teaching models. With the joint efforts of all parties, these two models may become an important aspect of improving the ability of STEM teachers. At the same time, we call on teachers and researchers to actively practice and improve the four teaching models proposed in this study in future STEM education. With more empirical evidence, we can learn in which model allows students to benefit more from STEM education. Teachers can also make more informed choices when designing STEM courses.

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Ethical Approval

This paper does not contain any studies with animals performed by any of the authors, and the cases are anonymous, thus we did not apply for ethical approval from any ethics committee.

Availability of Data and Materials

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

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