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# The impact of STEM curriculum on students' engineering design abilities and attitudes toward STEM

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## Abstract

While it has been recognized that science, technology, engineering, and mathematics (STEM) education requires an interdisciplinary approach, integrating multiple subjects in a meaningful way remains challenging for teachers. This study aimed to design a STEM curriculum, emphasizing explicit and continuous scaffolding of students' reflection on scientific and engineering knowledge. The primary goal was to foster knowledge integration in their engineering designs and enhance their attitudes toward STEM. The study involved fifty tenth-grade students who were guided to discuss and reflect on relevant scientific and engineering knowledge and to apply mathematics for data collection and analysis during the design of their technology products. The research instruments included an assessment of the progression of knowledge integration in students' engineering designs through student journals and pre- and post-test surveys on attitudes toward science, technology, engineering, and the learning environment. The results reveal that the introduction and explicit scaffolding students' reflection on scientific and engineering knowledge led to a gradual improvement in knowledge integration within their engineering designs. Students also significantly enhanced their attitudes toward STEM and the learning environment compared to the general school curriculum. This study contributes to interdisciplinary learning that promotes the integration of scientific and engineering knowledge in students' engineering design processes, and to interdisciplinary assessment that evaluates students' knowledge integration across learning progressions and outcomes.

**Keywords** STEM education · Interdisciplinary teaching · Engineering design · Engineering practice · High school students

## Introduction

There is growing concern about improving science, technology, engineering, and mathematics (STEM) education to boost students' interest in STEM and to improve the number and quality of the STEM global workforce. While STEM education has been recognized as

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an interdisciplinary approach, meaningful integration of multiple subjects remains difficult for educators (Bell, 2016; de Vries, 2018; English, 2016; Kertil & Gurel, 2016; Margot & Kettler, 2019; Radloff & Guzey, 2016). Some researchers have argued that the disciplines in STEM education are taught independently (Lin, 2018). Most K–12 curricula are more focused on the process of making technology and the product of this process than on the ways to apply science and mathematics to engineering processes to develop the final technological product.

Accordingly, this study aims to propose an innovative STEM curriculum that not only better integrates different disciplines but also enhances students' attitudes toward STEM. To enhance interdisciplinary learning in the STEM curriculum, students were explicitly scaffolded to involve relevant scientific and engineering knowledge and employ mathematics to collect and analyze data in their engineering practice when designing technology products.

## STEM curriculum design

STEM education has frequently been regarded as the teaching of four independent disciplines without any emphasis on the importance of their integration. Two approaches to the integration of STEM education were proposed by Moore and Smith (2014): context and content integration. The most significant difference between these modes lies in the role of the discipline of engineering in the curriculum. In context integration, engineering is regarded as a teaching method, and it is integrated with science, technology, and mathematics. In these curricula, engineering is employed as the context for teaching the science concepts. Hence, assessments focus on the results of students' science content learning (Anwar et al., 2022; Cunningham et al., 2020). However, in content integration, engineering is considered one of the learning goals, and the curriculum concentrates more on the process of teaching and learning engineering.

Since the emphasis on the integration of multiple disciplines in STEM education has gradually increased over time, most current STEM curricula are designed based on content integration between science and engineering. These STEM curricula have adopted the approaches of scientific inquiry, project-based learning, problem-based learning, or design-based learning to engage students in designing, creating, and testing technological products such as tumblewing gilders, rescue boats, bumper cars, circuits of light-emitting diodes, and astronomical models (Bartholomew, 2017; Dare et al., 2017; Eisenkraft & Chen Freake, 2018; Marshall & Harron, 2018; Wilhelm et al., 2019). These curricula usually start by introducing scientific concepts or principles underlying the design of certain technological products, which students are then required to apply while making these devices. Finally, the curriculum requires students to change or adjust their devices to enhance their final products.

Existing STEM curricula typically follow the conventional engineering processes, encompassing problem identification, idea exploration, and the stages of design, creation, testing, evaluation, and improvement of solutions. However, these approaches often present significant challenges in terms of promoting interdisciplinary learning and developing interdisciplinary assessment.

First, traditional STEM curricula usually introduce scientific concepts at the outset and then require students to begin their own engineering designs without further scaffolding by engaging in reflections on previously learned scientific concepts. Therefore, this type of curriculum generally lacks guidance to scaffold students to continuously integrate their ideas across different disciplines throughout the curriculum. As a result, students may continue to adopt a trial-and-error approach to making products instead of examining problems or evaluating and improving their designs from a scientific point of view. Although researchers have recognized the value of interdisciplinary teaching in STEM curricula (Falloon et al., 2020), the disciplines are still taught independently, not integrally. Vasquez et al. (2013) suggested that interdisciplinary STEM teaching, which involves students learning concepts and skills from more than two integrated disciplines, helps to deepen their knowledge and skills.

To address the lack of interdisciplinary learning in existing STEM curricula, the present study adopted the 6E (engage, explore, explain, engineer, enrich, and evaluate) teaching model proposed by Burke (2014) to design a STEM curriculum that emphasizes the integration of science and engineering into several appropriate stages of the curriculum and guides students in developing, evaluating, and revising their engineering designs from a scientific perspective. In this curriculum, students were scaffolded to reflect on their scientific knowledge continuously in several stages of their engineering design, instead of only at the beginning of the curriculum. Reflection on scientific concepts was employed as a tool to assist students to better develop, evaluate, and enhance their products during the engineering process.

Second, these existing curricula often evaluate students' learning performance according to their conceptual learning outcomes or final products, which may have been enhanced through trial and error. A recent review of assessing students' learning in STEM has pointed out the difficulties of interdisciplinary assessment, because current methods focus on teaching and assessing conceptual understanding in a single discipline without paying attention to the application of knowledge or integration of various types of knowledge into problem solving (Falloon et al., 2020; Gao et al., 2020). The core objective of the curriculum—the cultivation of interdisciplinary thinking in students' engineering designs—is not assessed. Hence, a better assessment should be developed to evaluate the interdisciplinary thinking and progress of students' learning.

In this study, to address the issue of interdisciplinary evaluation, a formative assessment approach was utilized to assess students' learning progression at different stages of the curriculum by observing their evolving ability to apply scientific and engineering knowledge to enhance their engineering designs. In contrast to traditional assessments that focus solely on final products, this approach provided insights into the dynamic process of knowledge integration.

Finally, a new scenario was designed to allow students to apply their understanding of the multiple disciplines learned in class to address new problems and design innovative technology. This assessment not only allowed continuous monitoring of how students integrated scientific and engineering knowledge across the curriculum, but also measured their ability to apply interdisciplinary thinking to a new context.

## 6E instructional model

The 6E teaching model, proposed by the International Technology and Engineering Educators Association (Burke, 2014), was designed not only for the cultivation of inquiry and problem-solving skills but also for emphasizing interdisciplinary integration in STEM. It comprises six different phases of inquiry: (1) engage students in the learning content, (2) explore relevant phenomena and materials, (3) explain underlying scientific concepts, (4) engineer the product, (5) enrich students' knowledge with application of their understanding, and (6) evaluate students' learning.

There are several examples the 6E instructional model being employed in teaching STEM curricula (Chung et al., 2018; Lin et al., 2020; Love & Deck, 2015). Love and Deck (2015) developed an ocean platform engineering design challenge based on the 6E instructional model that required students to use relevant scientific knowledge regarding earthquakes, tsunamis, kinetic energy, potential energy, and buoyancy combined with relevant engineering knowledge on structures and materials to design an offshore structure that can withstand ocean waves and deposits. The curriculum first engages students with a tsunami video then asks them to design simple buildings. These building are then repeatedly redesigned and modified with data and the modifications recorded each time so as to determine the final product and discuss the reasons behind the different results. The final Enrich stage includes a deep discussion on topics such as the relationships between building structures and ocean waves, environmental impacts, and the problems in the positioning of non-fixed offshore buildings.

Lin et al. (2020) developed an eight-week curriculum based on the 6E instructional model that centers on the design of airdrop rescue devices. The curriculum was shown to positive impact students' attitudes toward technology and their technological inquiry abilities. It starts by engaging students by describing the content of the activity and guiding them to explore their previous experience and preliminary ideas related to the topic. Next, the curriculum repeats the stages of Explain, Engineer, and Evaluate several times. Students use related principles or experiences to explain and engineer the devices and evaluate their performance. The teacher explains the principles underlying the design and helps students identify any problems with the devices, after which students discuss the problems and make the needed improvements to their devices. For the Enrich stage, a more complex task is proposed to further challenge students to design a device to reach the goal. Finally, students improve their devices and evaluate their performance.

While the above example employed 6E curriculum in a different way, the results revealed that students were motivated during the Engage stage and that the Explore stage allowed students to situate themselves in a scenario and encouraged them to think. Next, students cycled through the steps of designing, testing, and evaluating their device in the Explain, Engineer, and Evaluate stages. The Enrich stage encouraged them to apply what they had learned to a more complex situation.

In order to further enhance the knowledge integration in the 6E curriculum, the design of the study attempts to make more explicit and continuous connections between different disciplines based on the sociocultural theory perspective (Vygotsky, 1978), which suggests that learning occurs through social interaction. In science education, scaffolding has been employed in social interaction to support students' learning of concepts or skills (Saleh et al., 2020; Sezen-Barrie et al., 2020). Therefore, this study proposed further revision of the curriculum design to add continuous and explicit scaffolding of students' reflection on appropriate scientific and engineering knowledge in the Engineer, Enrich, and Evaluate stages to encourage students to develop, examine, and improve their devices. The comprehensive integration of science and engineering allows students to consider problems that occur during the engineering design process from different perspectives, thereby promoting their ability to engage in more realistic and interdisciplinary thinking at the micro level (Tytler et al., 2022).

In this study, in the Engineer stage, instead of mimicking the sample product they observed, students were asked to reflect on the scientific knowledge they discussed in the Explain stage. In the Evaluate stage, students also were asked to evaluate their design results and consider possible directions for improvement based on learned scientific and engineering knowledge. In the Enrichment stage, students were asked to apply what they had learned about scientific and engineering knowledge to design and create new technology in a more complex situation. These reflections are expected to promote students' knowledge integration as they contemplate how the problems can be solved through the acquired scientific or engineering knowledge.

## Attitudes toward STEM

STEM education has been actively promoted in an attempt to motivate students to engage in related career fields currently facing talent shortages. Thus, research has been conducted to evaluate the extent to which students' interest in STEM careers is stimulated through STEM education (Guzey et al., 2014). Studies have revealed that if students either exhibit a positive attitude toward certain subjects or believe that the subjects will be helpful to them in the future, after completing STEM education their willingness to engage in the corresponding field and career also increases (Beier et al., 2019; Maltese & Tai, 2011). Therefore, even if a particular course does not significantly improve students' willingness to choose a certain career, it can indirectly affect their future choices by enhancing their interest in and attitude toward the relevant subjects. Surveys have investigated whether STEM curricula affect students' attitudes toward disciplines in STEM and their willingness to engage in careers in related industries (Beier et al., 2019; Hans & Carpenter, 2014; Unfried et al., 2015; Vennix et al., 2018).

Compared to European countries, America, and Australia, the talent shortage in STEM-related fields is not as acute in Taiwan. However, to enhance the quality of STEM talent and the nation's technological competitiveness, the cultivation of talents with interdisciplinary capabilities is critical in Taiwan (Cheng & Lo, 2022). Therefore, it is even more essential to investigate students' learning attitudes toward STEM fields and their perceptions of interdisciplinary teaching and learning environments after they have experienced this STEM curriculum.

This study focuses on investigating students' learning attitudes. Existing research on students' learning attitudes usually focuses on two aspects: attitudes toward various STEM fields and attitudes toward the learning environment. The questionnaire developed by Unfried et al. (2015) focused on the former, whereas that developed by Vennix et al. (2018) focused on the latter and Hans and Carpenter (2014) focused on both. The findings of these three studies are presented below.

Vennix et al. (2018) concluded that students exhibited positive learning motivation during STEM activities and positive attitudes toward STEM's social implications. One of the major findings is that the differences in students' motivation and attitudes across different activities were due to the curricula contents. Students' attitudes were positively related to their motivation, and they showed a preference for personally relevant activities and for short projects or workshops. With this in mind, the STEM curriculum in this study will be designed based on topics that are relevant to technology in students' daily lives and can be applied to design products that can solve everyday problems. The length of the curriculum is limited to three hours.

Due to a shortage in professional talent in STEM subjects in the United States, Unfried et al. (2015) developed a survey to investigate attitudes toward and professional interests in

STEM careers among grade 4–12 students. The survey focused on four major areas: mathematics, science, engineering and technology, and 21st-century skills. The section on 21st-century skills included critical thinking, communication, problem-solving, and self-management skills. Our study adopted items from only three of these areas—science, engineering, and technology—due to our STEM curriculum largely focusing on integrating science and technology into the design of technology products with less mathematics involvement. Moreover, seeing that our research is interested only in the impact of our STEM curriculum on students' learning attitudes toward STEM and 21st-century skills are not the focus of the study, we did not include the items related to this area in our survey.

In contrast, South Korea does not suffer from a talent shortage but faces the challenge of students' low self-confidence and motivation to participate in science- and mathematics-related subjects despite their superior academic performance (Han & Carpenter, 2014; Mullis et al., 2008). To resolve this issue, the South Korean government has begun implementing STEM education. Han and Carpenter (2014) proposed a survey to ascertain motivations related to STEM curricula that covers five major areas: self-regulated learning, collaborative learning environment, interdisciplinary learning environment, technology-based learning, and hands-on activity. The survey was conducted with 785 South Korean middle school students after completing the STEM curriculum. The results revealed positive attitudes toward these five dimensions. Unfortunately, although the results of the survey revealed positive attitudes post-STEM curriculum, due to the absence of a pre-test, students' attitudes before and after the curriculum could not be compared to explore possibilities for their enhancement in class. As a result, this study selected questions from the areas of interdisciplinary learning environment, technology-based learning, and hands-on activity in Han and Carpenter (2014)'s survey, which allow us to investigate attitudes before and after our STEM curriculum to determine whether it enhances students' learning attitudes toward science, engineering, and technology, and the learning environment.

This study aimed to develop a STEM curriculum with a primary focus on scaffolding students' reflection on their scientific and engineering knowledge throughout the process of designing and enhancing flat speakers. In this study, explicit scaffolding refers to the instructor guiding students in utilizing their acquired scientific and engineering knowledge as cognitive tools throughout their entire engineering practice. The goal was to investigate the progression of students' interdisciplinary knowledge integration, facilitated by teachers' scaffolding of reflection at different stages of the engineering design process. The study sought to explore the impact of teaching methods that integrate scientific and engineering knowledge on students' engineering design and their overall attitudes toward STEM. Our investigation addressed the following research questions:

1. How do students' engineering designs evolve throughout the implementation of the curriculum?
2. To what extent do students incorporate their scientific and engineering knowledge in the engineering designs within the designed curriculum?
3. How does participation in the designed curriculum influence students' attitudes toward STEM?

## Methodology

This innovative STEM curriculum centered on the development of a simplified version of flat speakers. In recent years, innovative flat speakers have emerged, finding applications in various forms such as wallpaper, oil paintings, pillows, et cetera. In this STEM course, students would finally make a simplified flat speaker, with a detailed structure in Fig. 1. The curriculum involves the construction of flat speakers using conductive wires or tape on materials like electric tape or a paper card. In comparison to traditional speakers, flat speakers are notably flatter. Despite this distinction, the fundamental principle underlying sound generation in both flat and traditional speakers shares similarities. A varying electric current, generated by the sound source, flows through a coil of wire. This current generates an alternating magnetic field, which in turn alternately attracts and repels a stationary magnet, resulting in vibrations that ultimately produce sound. The classroom-friendly example of flat speakers is available for adoption through the High-Low Tech Group at the MIT Media Lab (https://highlowtech.org/).

Flat speaker design was chosen as the topic for the STEM curriculum rather than a traditional stereo speaker design for three reasons: First, flat speaker technology is a new technology and can be integrated with materials used in daily life, such as wall picture frames, greeting cards, cloth, and artworks. Second, due to the broad application of flat speakers, the curriculum can be designed to promote students' learning interests and foster their creativity in finding ways to integrate flat speakers into daily life and use them to address common problems. Third, making a flat speaker is technically easier for students than making a stereo speaker. Making flat patterns using copper tapes or other conductive materials takes less time than making coils, so the technical difficulties involved in the process are reduced, making it easier for students to troubleshoot problems. Accordingly, students focus more on reflecting on the scientific and engineering knowledge they have acquired in their engineering design process.

In short, this curriculum not only provides students a deeper understanding of the science and engineering of electricity in new technologies but also makes these new technologies more accessible to students to foster their interests, capabilities, and creativity in developing their own new technologies.

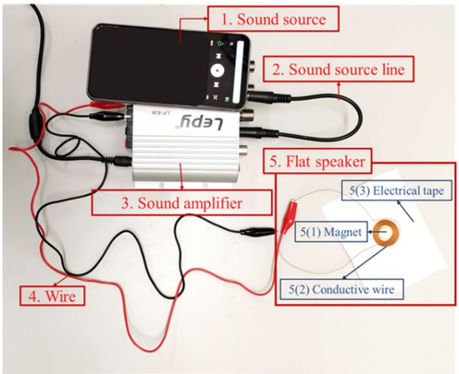


**Fig. 1** Structure of a Simple Flat Speaker

## Participants

A total of 50 tenth-grade students were voluntarily recruited from high schools in Central Taiwan (28 male, 22 female). Students voluntarily signed up to participate in this experimental curriculum through school announcements. They learned concepts related to electromagnetism, including the magnetic effect of an electric current, electromagnetic induction, and the relationship between electricity and magnetism.

This STEM curriculum was implemented within a university-based after-school program, and participants volunteered for these extracurricular activities. As a result, they may not be representative of all students in Taiwan, as they are self-selected individuals with a higher interest in science learning.

## STEM curriculum design based on 6E

This curriculum design was based on the 6E teaching model developed by Burke (2014). In the curriculum activities, students conducted reverse engineering on traditional stereo speakers and applied a similar rationale to design innovative flat speakers. They also learned about scientific models of sound waves and electromagnetic force, which were employed to design, make, and revise their own flat speakers over the course of seven activities. Finally, the students designed and created holiday cards using the scientific and engineering knowledge they had acquired. This flat speaker curriculum took a total of three hours to complete. The corresponding teaching objectives for each STEM field explored in this course are listed in Table 1.

An overview of the seven activities is given in Table 2. Throughout these sessions, students were introduced to the structure and materials of stereo speakers, as well as scientific models of sound waves and electromagnetic force. Importantly, students received explicit scaffolding to consistently reflect on this engineering and scientific knowledge, guiding them in the creation, evaluation, and modification of their flat speakers. In this curriculum, the initial activity provided students with the opportunity to brainstorm flat speaker structures based on their pre-existing ideas. Following the second activity, students were introduced to and prompted to reflect on the engineering knowledge acquired from the stereo speaker to design their own flat speaker. The third activity introduced the scientific concepts of sound waves and the model of electromagnetic force. After that, they were explicitly scaffolded to reflect on both scientific knowledge and engineering knowledge to develop, evaluate, and enhance their products. For a more comprehensive understanding of

**Table 1** Corresponding Teaching Objectives for Each STEM Field

| Science | Model of sound wave; model of electromagnetic force |
|---|---|
| Technology | Flat speakers at the maximum volume; the application of flat speakers |
| Engineering | The structure and materials of stereo speakers; design and build physical models of flat speakers; evaluation and improvement of the flat speakers; the use of decibels; the method of connecting the flat speaker with the amplifier and the sound source; synthesizing data and knowledge in the trial process |
| Mathematics | Measure decibels and plot data function charts |

**Table 2** Flat Speakers Activities

| Teaching activities | Activity content |
|---|---|
| Activity 1 | **Brainstorming about Flat Speaker Structure:** It Initiated with a brainstorming session on flat speaker structure, sparking interest by comparing the appearance and function of traditional and flat speakers. Students drew structure diagrams and recorded the scientific principles underlying these audio devices |
| Activity 2 | **Disassembling a Real Stereo Speaker:** It Involved disassembling a real stereo speaker to observe internal components and functions. Students revisited structure diagrams, incorporating newfound insights into flat speaker designs |
| Activity 3 | **Explaining the Magnetic Effect of an Electric Current:** It focused on the explicit scaffolding students' reflection on the scientific model of sound and the magnetic effect of an electric current. Students discussed how sound is transmitted through speaker wires, explored the relationship between the solenoid and the magnet in stereo speakers, and applied this knowledge to revise flat speaker designs |
| Activity 4: | **Making a Flat Speaker:** Students were asked to make and revise their flat speakers based on their scientific knowledge of electromagnetic force and their engineering knowledge of the essential components of a stereo speaker. Examples of flat speakers that students tested are displayed in Fig. 2 |
| Activity 5: | **Explaining the Factors that Affect Speaker Volume:** Students predicted and explained the factors affecting the interaction between the electromagnet and the magnet in a speaker, which was explicitly scaffolded to reflect on scientific knowledge |
| Activity 6 | **Discussing and Testing the Factors Affecting Speaker Volume through Experimentation:** Students were directed to experimentally explore factors influencing speaker volume. This process allowed them to assess the consistency and inconsistency between their scientific predictions and the engineering testing outcomes. This reflective exploration of the interplay between scientific and engineering knowledge served to strengthen the integration of interdisciplinary knowledge |
| Activity 7: | **Designing a Holiday Card with Flat Speakers with Maximum Sound Volume:** Students designed holiday cards with flat speakers, creatively applying the integrated knowledge they had learned. They assessed their designs based on scientific models and engineering knowledge. An example of a holiday card that was tested is presented in Fig. 3 |

the implementation of curriculum, including detailed illustrations and scaffolding methods based on the 6E model, see Appendix 1.

## Research instruments

The research instruments included an assessment of the progression of students' engineering designs in student journals and a survey concerning students' attitudes toward science, technology, engineering, and the learning environment using a pre- and post-test.

### Assessment of students' engineering designs

To continuously observe the progression of students' engineering design during this STEM curriculum, students were asked to record their structural drawings of the designs of their loudest flat speakers and the scientific concepts and reasons underlying their designs in Activities 1, 2, 3, and 7. This progression can reveal how learning the interdisciplinary

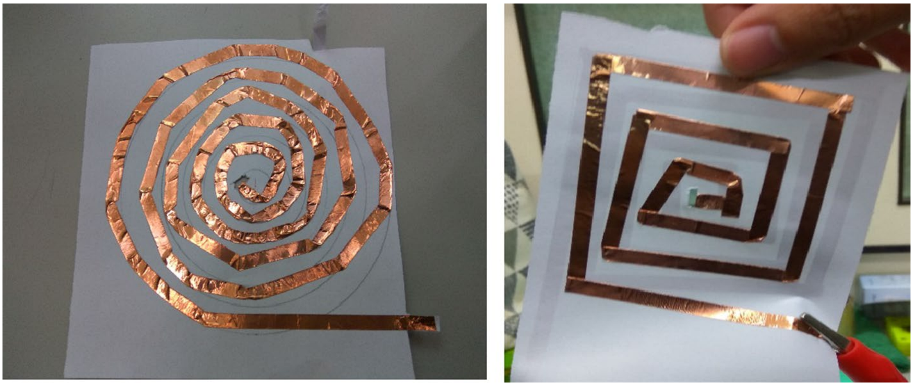
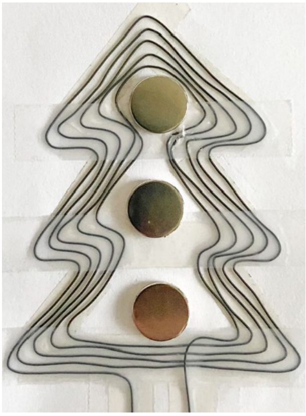


**Fig. 2** Examples of flat speakers engineered in Activity 4

**Fig. 3** An example of a holiday card created with a flat speaker in Activity 7



thinking of scientific and engineering knowledge can enhance their engineering designs of flat speakers in different stages. Four distinct stages can be identified: (1) before students learn scientific and engineering knowledge in Activity 1, (2) after conducting reverse engineering of stereo speakers in Activity 2, (3) after learning scientific models in Activity 3, and (4) after evaluating and testing products based on different variables with reflections on learned scientific and engineering knowledge in Activity 7.

## Student attitude survey about science, technology, and engineering

The purpose of this study is to investigate students' attitudes toward science, technology, and engineering before and after this STEM curriculum. Additionally, we investigated the differences between students' perceptions of their schools' general science curricula and this STEM curriculum. Accordingly, students took the survey before and after the STEM curriculum to identify the differences between their attitudes.

The survey items were adapted from established sources, Han and Carpenter (2014) and Unfried et al. (2015), demonstrating robust internal consistency (0.766 to 0.92). Initially chosen by three education experts specializing in physics, engineering, and technology,

**Table 3** Student Attitude Survey about Science, Technology, and Engineering

| |
|---|
| *Technology* |
| Thanks to technology, there will be greater opportunities for future generations |
| I have the technical skills I need to use technology |
| I will keep up with important new technologies |
| I will frequently play around with technology |
| *Engineering* |
| Thanks to engineering, there will be greater opportunities for future generations |
| I like to imagine creating new products |
| If I learn engineering, then I can improve things that people use every day |
| I am interested in what makes machines work |
| Knowing how to use math and science together will allow me to invent useful things I believe I can be successful |
| *Science* |
| Thanks to science, there will be greater opportunities for future generations |
| I am sure of myself when I do science |
| Knowing science will help me earn a living |
| I am sure I could do advanced work in science |
| I feel good about myself when I do science |
| *Learning Environment* |
| I can solve problems better by doing activities |
| The activities we do in classes are useful for learning |
| I feel involved in my work through the activities |
| I would like to do hands-on activity sometime |
| Hands-on activities really make sense to me |

the items align with the research questions. For individual STEM fields, the survey covers attitudes and learning attitudes. Regarding learning environments, it assesses students' attitudes towards activities in the general science curriculum (pre-test) versus the STEM curriculum (post-test). The survey was translated into Chinese to promote inclusivity and accommodate local students who are more proficient or comfortable in Chinese, thereby eliminating potential language barriers. The survey underwent iterative revisions based on student interviews to enhance clarity. Finally, nineteen survey items were selected, aligning closely with the study's objectives.

In our present study, the internal consistency of each scale ranged from 0.72 to 0.90. The survey required students to evaluate their attitudes toward STEM on a 5-point Likert scale. The survey items in Table 3 include four categories: attitudes toward science, technology, engineering, and the learning environment. Given the fact that this curriculum emphasizes the integration and application of science, technology, and engineering, mathematics is only involved in the measurement and comparison of the collected data. Since students only learned about the qualitative reasoning of scientific models of electromagnetic force, students' attitudes toward mathematics were not evaluated. Furthermore, in terms of learning environment, we expect to explore the differences between students' participation in and perceptions toward the learning environment of traditional curricula typically provided by schools and this STEM curriculum.

**Table 4** Four Levels of Engineering Design

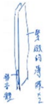
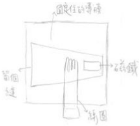
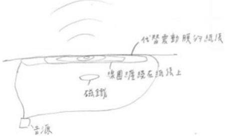
| Levels | Definition | Example |
|---|---|---|
| Level 1 | The engineering design describes the appearance without describing the inner components and underlying scientific principles | The student's drawing and description includes a structure of a compact membrane, which functions to vibrate for emitting sound, and a sound-emitting body, which functions to produce sound  |
| Level 2 | The engineering design labels the name, position, and the interactions of the key sound-producing components | The student's drawing and description includes the main components, including magnets, coils, and membranes, along with their respective positions, but he did not articulate the scientific principles behind them  |
| Level 3 | The engineering design not only indicates the internal components but also provides scientific concepts or principles underlying the utilization of the components | The student's drawing and writing includes and outlines the functions and principles of the coil, magnet, and sound source. It involves the sound source providing alternating current to the coil. The coil generates magnetic fields through the alternating current, interacting with the magnet to produce attraction and repulsion  |

**Table 4** (continued)

| Levels | Definition | Example |
|---|---|---|
| Level 4 | The engineering designs revise and improve the components in accordance with the engineering objectives. Students can describe the scientific concepts or principles underlying the revisions | The student's drawing and description includes the functions and principles of the coil, magnet, and sound source. It states that current from the sound source passes through the coil, generating a magnetic field and causing vibrations between the coil and magnet, resulting in the production of sound waves. Additionally, in order to maximize the loudness of the speaker, she increases the number of coils, places the innermost coil closer to the magnet, and add five magnets to the center of the coil<br><br> |

## Data analysis

### Analysis of students' engineering designs

According to the researchers' definition of interdisciplinary competence, students should be evaluated based on whether they can employ knowledge and methods from multiple disciplines (Song & Wang, 2021; Wang & Song, 2021; You et al., 2018). In this study, in order to investigate students' interdisciplinary learning, their engineering designs of flat speakers from Activities 1, 2, 3, and 7 were analyzed and classified based on the degree to which they showed the integration of scientific and engineering knowledge and practice in the designs throughout the curriculum, thereby enhancing their evaluations and revisions of their technology products. The designs were classified into four levels according to whether the students could identify major sound-generating components, describe the scientific principles of sound-generating components, and illustrate the components and underlying scientific concepts that would enable their speakers to achieve maximum volume. The definitions and examples of the four levels are listed in Table 4. In order to classify all the designs according to level, the authors discussed students' engineering designs throughout the curriculum until reaching stable coding and interpretations. The discrepancies in the coding were discussed until consensus was reached.

### Analysis of the student attitude survey

This study compares the pre- and post-test scores of the student attitude surveys about science, technology, and engineering to study whether the students' attitudes change as a result of the STEM curriculum. Furthermore, this study compares students' attitudes toward general science learning school environments in the pre-test and toward this innovative STEM curriculum in the post-test. A paired sample t-test was conducted to compare the means of the pre- and post-tests to explore the significant changes in students' attitudes.

## Results

### Progression of students' engineering designs

The distribution of the students' engineering design levels is shown in Table 5. Students' engineering designs gradually progressed mostly from Level 1 in Activity 1 to Level 4 in

**Table 5** The Distribution of Levels of Students' Engineering Designs

| | Activity 1 | | Activity 2 | | Activity 3 | | Activity 7 | |
|---|---|---|---|---|---|---|---|---|
| | N | % | N | % | N | % | N | % |
| Level 1 | 40 | 80 | 2 | 4 | 0 | 0 | 0 | 0 |
| Level 2 | 6 | 12 | 18 | 36 | 10 | 20 | 7 | 14 |
| Level 3 | 2 | 4 | 16 | 32 | 19 | 38 | 5 | 10 |
| Level 4 | 2 | 4 | 14 | 28 | 21 | 42 | 38 | 76 |
| Average Levels | 1.32 | | 2.84 | | 3.22 | | 3.62 | |

Activity 4. The average mean scores of the students' engineering design progress ranged from 1.32 to 3.62.

In Activity 1, students were asked to brainstorm the structure of flat speakers with maximum volume based on their pre-existing ideas after being introduced to innovative technologies involving flat speakers, but without explanation of their underlying structure and scientific principles. Most students (80%) could only portray the appearance of the speaker in their engineering designs at Level 1.

In Activity 2, students engaged in reverse engineering of stereo speakers. They were tasked with observing and inspecting the internal structures and functions, laying the groundwork for the development of a flat speaker. Throughout this process, students were guided to reflect on the engineering knowledge gleaned from the stereo speaker, informing the subsequent design of their own flat speakers. Most students (68%) had engineering designs that reached Level 2 and Level 3. Approximately 36% of students progressed to Level 2, indicating that they could describe the appropriate sound-generating components, while 32% of students progressed to Level 3, demonstrating that they could not only include the appropriate components but also explain the underlying scientific explanations. This means that dissembling a stereo speaker without discussing the related scientific concepts may prompt students to think about the essential components and scientific concepts underlying their engineering designs.

In Activity 3, students and the instructor engaged in discussions and explanations of the scientific concepts underpinning speakers. The instructor played a pivotal role by explicitly scaffolding students' reflection on the scientific model of sound and the magnetic effect of an electric current. This guided reflection aimed to facilitate the revision and improvement of their flat speakers. Most students (80%) had engineering designs that reached Level 3 and Level 4. Specifically, 38% of students progressed to Level 3, showing they could identify appropriate components and understand the underlying scientific explanations. The remainder (42%) further progressed to Level 4, which involved enhancing their speakers based on the engineering objectives and the underlying scientific concepts. This finding reveals that although Activity 3 only provided opportunities for the teacher and students to explain the scientific concepts, the numbers of students whose engineering designs reached Level 4 progressed steadily from two persons in Activity 1, to 14 persons in Activity 2, to 21 persons in Activity 3. Furthermore, no students' structure drawing failed to progress past Level 1. This means that scaffolding students' reflection on scientific and engineering knowledge may encourage students not only consider the scientific concepts underlying their designs, but also further enhance their designs.

During Activities 4, 5, 6, and 7, students were asked to make and refine their flat speakers using scientific knowledge of electromagnetic force and engineering knowledge from stereo speakers. They predicted factors impacting electromagnet-magnet interaction, scaffolded to reflect on scientific knowledge. Following this, students conducted engineering testing on possible factors affecting speaker volume, providing an opportunity to evaluate the alignment and disparities between their scientific predictions and engineering testing outcomes. This reflective process enhanced the integration of interdisciplinary knowledge, fostering a deeper understanding of the interplay between scientific and engineering concepts. Ultimately, students were scaffolded to applied their integrated knowledge to creatively design holiday cards with flat speakers, evaluating designs based on scientific models and engineering knowledge. Accordingly, at the end of Activity 7, most students (76%) created engineering designs that reached Level 4. This finding reveals that Activities 4 to 7 continuously and explicitly scaffolded students' reflection on scientific and engineering knowledge during the engineering design process enabling most students to further revise

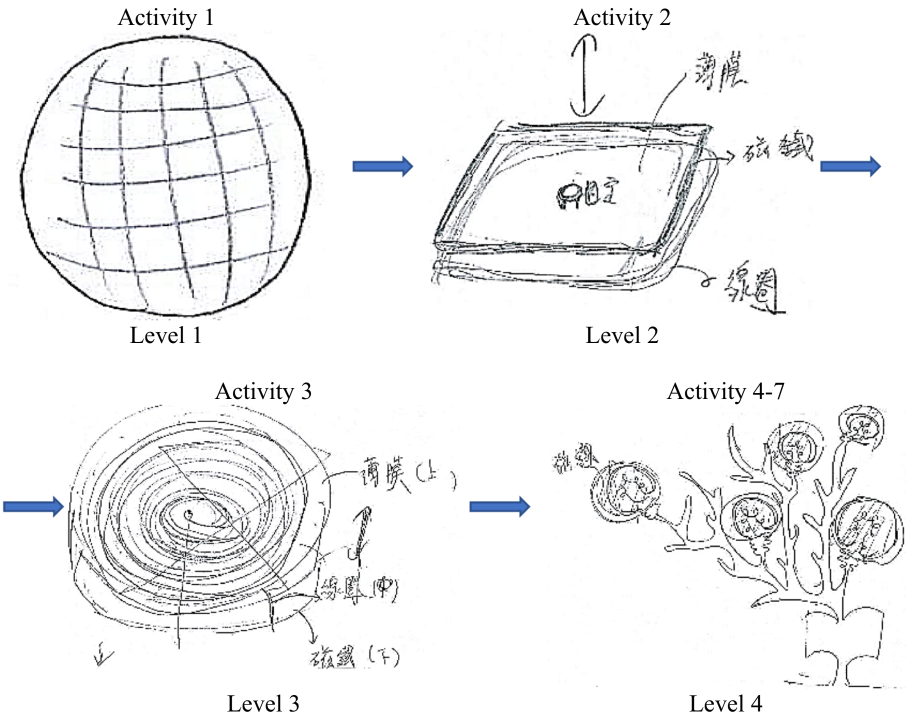


**Fig. 4** An example of the progression of a student' engineering designs

their flat speakers to achieve maximum volume, guided by a synthesis of scientific predictions and engineering testing.

## Knowledge integration in students' engineering designs

The following is an example of the progression of a student's engineering design in these seven activities. For example, as shown in Fig. 4, in Activity 1, the student drew the flat speaker with a tight cross surface. She only described this thin tight surface can vibrate to make sounds. Without describing the inner components and underlying scientific principles this design was classified as Level 1. In Activity 2, after the reverse engineering of stereo speakers, the student drew a thin film on top of a magnet and a square shape of coil to represent the main structure of a flat speaker and indicated that the vibration of the thin film produces sound (see the second picture in Fig. 4). Without providing any further explanation of how these components work, her design was classified as Level 2.

In Activity 3, after the student have introduced and asked to reflect on the key scientific concepts underlying the design of a stereo speaker, she started to revise her flat speaker as a thin film on top of a flat circular and spiral shape of coil and the magnet on the bottom (see the third picture in Fig. 4). In her worksheet, she illustrated that the coil needs to be wrapped around the diaphragm. The change in current in the coil would cause the attraction

**Table 6** Results of Paired Sample T-Test on Students' Engineering Design between Activities

| Improvement between the activities | Mean | S.D | *t* | *Sig* | Cohen's d |
|---|---|---|---|---|---|
| Activity 1 | 1.32 | 0.74 | 9.52*** | .000 | 2.51 |
| Activity 2 | 2.84 | 0.89 | | | |
| Activity 2 | 2.84 | 0.89 | 2.72** | .009 | 0.39 |
| Activity 3 | 3.22 | 0.72 | | | |
| Activity 3 | 3.22 | 0.76 | 3.30** | .002 | 0.47 |
| Activity 7 | 3.62 | 0.73 | | | |
| Activity 1 | 1.32 | 0.74 | 15.71*** | .000 | 2.23 |
| Activity 7 | 3.62 | 0.73 | | | |

** $p < .01$; *** $p < .001$

with the magnet to produce vibration, which would push the diaphragm to vibrate air and thus produce sound. Due to including the underlying scientific concepts and the main components, this structural drawing was classified as Level 3.

During Activities 4, 5, and 6, the student created a flat speaker. Then, they were asked to predict the factors that might influence speaker volume according to the learned scientific models, and tested these factors. During these activities, the class found that some of their predicted results based on their scientific models of electromagnetic force were not consistent with their engineering testing. For instance, according to their scientific models, they predicted that adding more magnets or more circular coil windings would enhance the volume of the flat speakers. Nevertheless, according to their engineering testing, there is a limitation to how much these numbers can be increased.

Accordingly, in Activity 7, the student finally designed her own holiday card with flat speakers at maximum volume (as depicted in the fourth picture of Fig. 4). On her worksheet, she clarified the underlying scientific models of her design, emphasizing the magnetic effects generated by the changing current in the coil interacting with magnets to produce sound. Furthermore, she illustrated several components of her flat speaker that lead to maximum sound volume. Due to the consideration of her previous engineering testing, her design reduced the number of coil windings but increased the number of circular coils. She indicated and positioned the inner circle of the coil close to the circumference of the magnets. Additionally, she limited the number of magnets under each circular coil to five. Given her reliance on both scientific models and their engineering testing results to maximize the volume of her holiday card, her engineering design was classified as Level 4.

**Table 7** Results of Paired Sample T-Tests of Pre- and Post-tests on Students' Attitude toward STEM

| Dimensions | Pre-test | | Post-test | | *t* | *Sig* | Cohen's d |
|---|---|---|---|---|---|---|---|
| | *M* | *S.D* | *M* | *S.D* | | | |
| Technology | 4.24 | 0.51 | 4.49 | 0.45 | 5.29*** | .000 | 0.52 |
| Engineering | 4.28 | 0.50 | 4.62 | 0.48 | 6.81*** | .000 | 0.69 |
| Science | 4.10 | 0.50 | 4.47 | 0.52 | 6.15*** | .000 | 0.73 |
| Learning Environment | 4.04 | 0.73 | 4.69 | 0.50 | 6.03*** | .000 | 1.04 |

***$p < .001$

Table 6 shows that through this STEM curriculum, students' engineering designs progressed from the lower mean score of 1.32 to the higher mean score 3.62. In Table 5, the continuous increase in the mean score indicates the students' continuous progression throughout the course. Paired sample t-tests revealed that the STEM curriculum overall significantly improved students' engineering designs, with gradual improvements in each stage. Cohen's (1988) definition of effect size for small, medium, and large, which are 0.2, 0.5, and 0.8, respectively, shows a large effect between Activities 1 and 2 and between Activities 1 and 7 and a medium effect between Activities 2 and 3 and between Activities 3 and 7. The results indicate that each activity was essential for students to improve their engineering designs—from a low level in which only the appearance or unessential components of the flat speakers were included—to the higher levels, in which they included and enhanced the essential components to achieve the engineering goals based on the underlying scientific concepts of the flat speakers.

## Progression of students' attitudes toward stem and stem learning environments

Paired sample t-tests were conducted on four major dimensions of the attitudinal survey, as shown in Table 7. The post-tests of the four dimensions were significantly higher than the pre-tests, with large effect sizes between 0.52 and 1.04. The results indicated that this STEM curriculum enhanced students' attitudes toward STEM, and that they preferred this STEM learning environment to their general classroom learning environment.

This STEM curriculum involving flat speakers enhanced students' attitudes toward certain aspects in four dimensions. Regarding technology, students' attitudes toward their technical skills for using technology ($t(49) = 2.65$, $p < 0.05$), and staying abreast of significant technological advancements ($t(49) = 5.03$, $p < 0.05$). However, no statistically significant improvements were observed in students' attitudes towards their appreciation for technologies offering greater opportunities for future generations ($t(49) = 1.95$, $p = 0.057$) and their willingness to play around with technology ($t(49) = 1.67$, $p = 0.10$). The lack of progress in these two aspects may be attributed to students' pre-existing high preferences, as indicated by the relatively high average mean scores ($M = 4.66$, 4.68) on the Likert scale.

Concerning engineering, students exhibited positive shifts in their attitudes, including an increased appreciation for engineering's potential to provide opportunities for future generations ($t(49) = 3.07$, $p < 0.05$), a heightened willingness to create innovative products ($\mathrm{t}(49) = 4.03$, $p < 0.05$), a greater inclination to acquire engineering-related knowledge for life improvement ($\mathrm{t}(49) = 3.28$, $p < 0.05$), and an amplified interest in machine mechanisms ($t(49) = 5.44$, $p < 0.05$). However, there was no significant advancement in students' attitudes towards recognizing the essential roles of science and mathematics in engineering application ($t(49) = 1.73$, $p = 0.09$). This lack of progress may be attributed to students' initially high pre-test scores ($M = 4.5$, $SD = 0.6$) or a potential oversight in explicitly addressing the crucial roles of science and mathematics in engineering process.

In the realm of science, students displayed improved attitudes across multiple dimensions, including a heightened appreciation for science offering opportunities for future generations ($t(49) = 2.42$, $p < 0.05$), increased confidence in engaging in scientific endeavors ($t(49) = 5.82$, $p < 0.05$), recognition of the significance of scientific knowledge in career pursuits ($t(49) = 3.40$, $p < 0.05$), a belief in their capacity to undertake advanced work in science ($t(49) = 3.62$, $p < 0.05$), and a sense of accomplishment when involved in scientific practices ($t(49) = 3.31$, $p < 0.05$).

In terms of classroom environment, students' attitudes toward the learning environment were positively influenced by the implementation of this STEM curriculum. In comparison to general science classroom instruction, students perceived that the STEM curriculum significantly improved their problem-solving abilities ($t(49) = 5.60$, $p < 0.05$), facilitated the acquisition of subject knowledge ($t(49) = 4.75$, $p < 0.05$), fostered a sense of involvement in their work ($t(49) = 5.31$, $p < 0.05$), increased their willingness to engage in hands-on activities ($t(49) = 3.56$, $p < 0.05$), and made hands-on activities feel more meaningful ($t(49) = 5.26$, $p < 0.05$).

## Discussion and implications

This study developed a STEM curriculum that explicitly scaffold students to engage in interdisciplinary thinking, by reflecting on scientific and engineering knowledge, as they developed, evaluated, and revised flat speakers. Positive results revealed improved engineering designs and enhanced STEM attitudes through continuous scaffolding. The contribution to STEM education by detailing a teaching approach fostering students' integration of scientific and engineering knowledge and an evaluation method assessing interdisciplinary learning progression. Building on our prior publication, this curriculum not only elevated students' attitudes towards STEM but also narrowed the gender gap (Cheng & Lo, 2022). These insights provide implication for educators and researchers seeking an effective method and an assessment to nurture and evaluate students' interdisciplinary learning in STEM.

## Progression of students' engineering designs

In this study, students' engineering designs demonstrated significant improvement across the STEM curriculum. Before the STEM curriculum, most engineering designs lingered at Level 1, merely describing flat speaker appearances. After disassembly and observation of stereo speaker components, their designs elevated to Level 2 or beyond, incorporating essential stereo speaker components into structural diagrams. After discussing scientific principles and being asked to apply them to reflect on designs, the majority of students advanced to Level 3 or higher. Students were able to articulate the scientific concepts underlying their designs. Through continuous, explicit scaffolding of scientific and engineering knowledge reflection, students created, evaluated, tested, and revised flat speakers, achieving Level 4. They were able to explain scientific concepts guiding structure diagram revisions to attain the engineering goal of maximizing volume.

### Importance of explicit scaffolding in STEM teaching

The results presented above demonstrate the effectiveness of the scaffolding approach within our STEM curriculum. The presented results underscore the effectiveness of the scaffolding approach in our STEM curriculum, facilitating explicit and continuous reflection on both scientific and engineering knowledge. It appears that simply asking students to design a product or introducing scientific and engineering knowledge at the beginning of curriculum is not sufficient to enhance most students' engineering designs. In other words, students may not spontaneously incorporate the provided scientific or engineering knowledge throughout their entire design process. This means that without a structured reflective framework, the introduction of scientific and engineering knowledge alone is insufficient. As suggested by Van Breukelen et al. (2017), in STEM education, explicit instruction on the underlying scientific concepts is crucial for meaningful integration in the design processes. Thus, this study highlights the critical need for explicit scaffolding in the reflection process for effective integration of scientific and engineering knowledge during engineering design.

However, most STEM curricula often lack interdisciplinary teaching that thoroughly integrates science and engineering. Most STEM curricula either employ the engineering design process as a context in which to teach students scientific concepts (Anwar et al., 2022; Cunningham et al., 2020) or they begin with reference to scientific concepts, followed by repeated engineering practice aimed at improving the finished product (Bartholomew, 2017; Eisenkraft & Chen, 2018; Lin et al., 2020; Love & Deck, 2015). Therefore, this study proposed a comprehensive activity process for the STEM curriculum. It not only guides students to reflect on and apply their knowledge in both engineering and science but also emphasizes the integration of the two domains to achieve engineering goals. This advancement in knowledge integration and interdisciplinary teaching aligns with the broader recommendations in STEM education literature, advocating for deepening students' knowledge and skills (Tytler et al., 2021; Vasquez et al., 2013; Walker et al., 2018).

## Micro-level integration in STEM teaching

Our interdisciplinary teaching extends beyond existing practices by integrating engineering and science at a micro-level, which has been less studied (Tytler et al., 2021). This STEM curriculum includes several stages, progressing from reverse engineering and scientific discussions to hands-on speaker construction and revision. Through these stages, students experienced explicit scaffolding for reflection on engineering and scientific knowledge, and ultimately explored the interplay between the two.

The integration of engineering and science occurred in several stages of this STEM curriculum. First, after reverse engineering of a stereo speaker and exploring its internal components, the students engaged in discussions about related scientific knowledge. They were prompted to reflect on the essential components of stereo speakers and the underlying scientific principles before constructing their own flat speakers. Second, to enhance speaker volume, students were guided to predict the factors that might influence the volume of their flat speakers according to the scientific model of electromagnetic force. Following predictions, students tested these factors, comparing the engineering testing results with their scientific predictions. In the final stage, students designed their own holiday card with a flat speaker, with explicitly scaffolding their reflection on the integration of scientific and engineering knowledge. This process not only allowed students to experience the benefits of applying scientific models and engineering knowledge in developing and revising their designs but also prompted discussions on the limitations of the scientific models when predictions didn't align completely with engineering testing outcomes.

Accordingly, this STEM curriculum provides a practical context for students to solve a real engineering problem and attain an engineering goal. Through scaffolding students' reflection on scientific and engineering knowledge, students not only engaged in the benefits of applying interdisciplinary knowledge in designing and revising their projects but also gained an understanding of how science and engineering can complement and reinforce each other.

### Assessment tool in STEM teaching

To assess the progression of students' engineering designs, we proposed an assessment tool that evaluates the integration of scientific and engineering knowledge at different stages of curriculum. Most existing STEM curricula assess students' progress in terms of their final technological products, which does not allow investigating whether students can actually apply scientific or engineering knowledge to their engineering designs, rather than relying on trial and error (e.g., Dare et al., 2017; Lin et al., 2020). This assessment tool goes beyond typical assessments that focus on final technology products, allowing teachers to track the dynamic progression of knowledge integration throughout the learning process. This method goes beyond evaluating students' learning outcomes in individual disciplines or their final technology products, as is done in existing STEM curricula (Bartholomew, 2017; Dare et al., 2017; Eisenkraft & Chen Freake, 2018; Falloon et al., 2020; Gao et al., 2020; Marshall & Harron, 2018; Wilhelm et al., 2019).

## Progression of students' attitudes toward STEM

The STEM curriculum has demonstrated positive impacts on students' attitudes across technology, engineering, science, and the classroom environment. While similarities exist in the overall positive trends, differences highlight specific areas of strength or potential improvement within each dimension. Statistically significant improvements were observed in students' attitudes towards their appreciation for engineering and science potential and their willingness to work with engineering and science. On the other hand, no statistically significant improvements were observed in students' attitudes towards their appreciation for technologies potential and their willingness to play around with technology. The lack of progress in these aspects may be attributed to students' pre-existing high preferences, suggesting that the study contributes more to enhancing students' confidence in their technological abilities than influencing their fundamental beliefs in technology.

Furthermore, no significant advancement was observed in students' attitudes towards recognizing the essential roles of science and mathematics in engineering applications. This lack of notable progress hints at a potential gap in explicitly emphasizing the interdisciplinary nature of these subjects within the context of engineering. While students engage in interdisciplinary learning in the STEM classroom, the absence of explicit emphasis on the interconnectedness between different disciplines may hinder their understanding of the pivotal roles science and mathematics play in engineering practice.

Moreover, the implementation of the STEM curriculum positively influenced students' attitudes toward the classroom environment. In comparison to general science classroom instruction, students perceived that the STEM curriculum significantly improved their problem-solving abilities, facilitated the acquisition of subject knowledge, fostered a sense of involvement in their work, increased their willingness to engage in hands-on activities, and made hands-on activities feel more meaningful. These results highlight the curriculum's effectiveness in enhancing not only subject-specific skills but also broader aspects of the learning experience, contributing to a more positive and engaging classroom environment. This aligns with the findings of Han and Carpenter (2014), who highlighted the positive impact of interdisciplinary learning environments on students' attitudes. Additionally, our previous research also suggests that this curriculum approach may help reduce the gender gap in students' attitudes toward technology (Cheng & Lo, 2022), contributing to the development of a more inclusive and female-friendly STEM curriculum.

Existing research underscores the importance of aligning teaching content with students' lives to enhance learning motivations and attitudes (Vennix et al., 2018). Accordingly, this study incorporated the design of technology products relevant to students' daily lives. Furthermore, the topic goes beyond a common engineering topic, e.g., making bridges, towers, or egg drop projects, which only mimic the design of technological products. This curriculum further encouraged students to employ their scientific and engineering knowledge to design innovative technology products that they could actually utilize in their daily lives, which made technology innovation more accessible to them. Although the emphasis on innovation was not explicit in the curriculum or assessment, students displayed a keen interest in integrating their knowledge into the creation of innovative technology products. Thus, future research could explore how the STEM teaching approach further enhances students' innovation and creativity in STEM education.

## Teaching implications for the STEM curriculum

This study has several teaching implications for interdisciplinary learning in STEM. First, the assessment of students' progression and knowledge integration is recommended. The existing STEM research review showed that STEM assessment usually focuses on the final products that students made or their knowledge in individual disciplines (Falloon et al., 2020; Gao et al., 2020). This research resolves the difficulties in interdisciplinary assessment and contributes to developing an evaluation method to assess students' learning progression and knowledge integration between science and engineering. Throughout this STEM curriculum, asking students to draw their engineering designs and detail the scientific knowledge underlying their component design and revision provides instructors with a clear picture of the progression of their integration of scientific and engineering knowledge.

Second, discussion and reflection on scientific and engineering knowledge should be explicitly scaffolded at various activity stages. The results of this research revealed the continuous improvement of students' knowledge integration in their engineering design when they were continuously and explicitly scaffolded to reflect on their scientific and engineering knowledge, instead of only introducing the related knowledge at the beginning of the curriculum. Therefore, the results suggest that scientific and engineering knowledge is employed as a tool when students design, evaluate, and revise their products. Students should be guided to constantly employ scientific and engineering knowledge to analyze and resolve engineering problems to achieve interdisciplinary thinking. Only introducing scientific knowledge at the beginning of the STEM curriculum may not encourage students to reflect their scientific knowledge in their engineering practice. Students may heavily rely on their intuition without scaffolding.

Third is the way of teaching knowledge integration in STEM. The curriculum design in this study illustrates a reciprocal relationship between science and engineering disciplines within the STEM framework, demonstrating their potential to support and complement each other. In this study, as students engaged in reverse engineering during their practical work, they began incorporating relevant engineering knowledge to assess and refine their products. Some students further gave greater consideration to the scientific principles underlying their designs. Through explicit scaffolding, as students were guided to articulate and reflect on the scientific knowledge supporting their designs, the majority demonstrated the ability to integrate both related scientific and engineering knowledge in evaluating and revising their products. The identified disparities between their scientific predictions and engineering testing outcomes prompted students to recognize the interplay between the two domains. This acknowledgment allowed them to leverage scientific knowledge for better predictions while acknowledging the limitations of scientific models through engineering testing. This synthesis of engineering testing results with scientific knowledge facilitated the creation of their final technology products. It has been recognized that engineering knowledge is not derived from science; it is distinct from scientific knowledge (Sheppard et al., 2007). Therefore, how scientific and engineering knowledge should be taught in engineering practice to better promote interdisciplinary learning requires further research.

## Conclusion

Recent STEM education has emphasized interdisciplinary learning, but how different disciplines were integrated in the STEM teaching remains unclear. This study proposes a STEM teaching approach and assessment, offering a method to integrate diverse disciplines and evaluate the progression of students' knowledge integration in engineering design.

The curriculum provides explicit scaffolding for students to reflect on their engineering and scientific knowledge throughout their design process, fostering the creation, evaluation, and revision of their technology products. Beyond enhancing interdisciplinary knowledge integration in engineering design, this teaching approach positively influences students' attitudes toward STEM and the learning environment. The study provides insights into teaching methods for interdisciplinary learning in STEM, while assessing students' interdisciplinary learning progression.

## Limitations and future research

While the study successfully demonstrates the positive impact of this STEM curriculum on students' engineering design abilities and attitudes toward STEM, it is essential to acknowledge certain limitations. Firstly, the curriculum took place in an after-school program within the university site and involved voluntary participation, highlighting a potential limitation. The self-selected nature of the participants may introduce a selection bias, as those who volunteer are likely to have a higher intrinsic interest in science and STEM-related activities. As a result, the findings may not be fully generalizable to the broader student population, raising questions about the external validity of the study. Future research could consider diversifying the participant pool to ensure a more representative sample and enhance the applicability of the curriculum to a wider range of students.

In addition, while the study highlights the positive impact of explicit scaffolding for student reflection on scientific and engineering knowledge, a limitation lies in the potential influence of time, the instructor's role, collaborative efforts with peers on the observed improvements. It is important to acknowledge and explore whether the enhanced understanding is solely a result of prolonged engagement with the problem or influenced by other protentional factors. Addressing this concern is essential for future research involving a control group for comparative analysis adds depth to addressing this concern. More rigorous investigations of the impact of explicit scaffolding on student understanding in STEM education are needed.

## Appendix 1

### Teaching activities based on 6E

The seven teaching activities and corresponding 6E teaching model progressed follows:

### Activity 1: Brainstorming about flat speaker structure

The first activity is the Engage stage in the 6E framework, which aims to enable students to connect their own experiences to the learning content to stimulate learning interest. At the beginning of the course, the teacher presented a stereo speaker that the students were familiar with and then played an exhibition video of new technologies created using flat speakers to arouse the students' curiosity and attention. Next, the instructor asked students questions to contrast traditional stereo speakers with this flat speaker technology. Finally, the instructor asked students to think about the physics concepts and rationale used in flat speaker design and to draw structure diagrams of flat speakers that they believe could produce the maximum volume.

### Activity 2: Disassembling a real stereo speaker

The second activity is the Explore stage in the 6E framework, which seeks to provide opportunities for students to develop their own experiences and understanding of the topic. In this study, actual stereo speakers were provided so that students could observe and examine the internal structure. Students were guided to observe the key components and functions inside the speaker, such as the winding of the coil, the position of the magnet (as tested by a paper clip), and the vibration of the coil inside the ring magnet after it is connected to a sound source. Finally, they were asked to revisit the concepts involved in the structure diagrams created in Activity 1 and to redraw the structure of a flat speaker that could produce the maximum volume.

### Activity 3: Explaining the magnetic effect of an electric current

The third activity is the Explain stage of the 6E framework, whose primary goal to guide students to rethink what they have learned by explaining the related concepts in the current context. The way in which sound is transferred through the speaker wire was discussed and explained by both students and instructors: sound is generated by the rapid vibration of an object and transmitted to the human ear through the medium and then converted into an electric current in the wire; this is like connecting a sound source cable to a phone to send sound waves to a speaker or amplifier in the form of electric current.

Next, the instructor introduced the concept of the magnetic effect of an electric current, which is the focus of the scientific models in this curriculum. The instructor first introduced the fact that a current-carrying wire produces a magnetic field using a solenoid as an example to demonstrate Ampère's right-hand grip rule of determining the direction of a current and a magnetic field. Then the instructor proposed the following situation for students to consider and discuss: if a non-movable magnet is installed on the side of the current-carrying solenoid, what would happen between the solenoid and the magnet if the value and direction of the current inside the solenoid are changed? Students discussed and concluded that when the solenoid in the speaker is connected to an alternating current, the magnetic field changes constantly. There is both attraction and repulsion between the solenoid and the magnet, which vibrates the diaphragm connected to the solenoid, thus generating sound.

Although the underlying principle of sound generation in both flat speakers and traditional speakers shares similarities, students were encouraged to use the interaction between the solenoid and the magnets in 3 dimensions in stereo speakers and to think about the interaction between their flat conductive wire pattern and the magnets in 2 dimension in flat speakers. Hence, after explaining and discussing the scientific model of sound and electromagnetic force as it applies to stereo speakers, students were encouraged to rethink whether the designs of the flat speakers they had produced in Activity 2 were reasonable in light of this scientific model. They were also expected to revise their flat speaker structure diagrams and reconsider their underlying scientific principles.

### Activity 4: Making a flat speaker

The fourth activity comprises the Engineer and Evaluate stages of the 6E framework. The purpose of the Engineer stage is to enable students to apply their understanding of scientific models to their engineering designs and consider whether their models would operate successfully. The purpose of the Evaluate stage is to enable students to assess whether their products function in line with their expectations and consider how to modify them.

First, the instructor provided a brief introduction to the experimental materials and the use of decibel meters and amplifiers. Then students shared the advantages and disadvantages of the individual structure diagrams from in Activity 3 within groups and designed one group structure diagram in detail, which was then engineered and tested. The teacher encouraged the students to analyze the factors that impacted the volume of their flat speakers, modify their products, and record their improvements based on their scientific knowledge of electromagnetic force and their engineering knowledge about the essential components of the stereo speaker. In the process of making and testing the flat speakers, students might encounter many difficulties and failures, including sticking wires, absence of sound, and low prototype volume. Finally, each group demonstrated their design, creation, and revision process to the entire class.

Examples of flat speakers that students tested are shown in Fig. 2. In order to make flat speaker, these students stick the copper tape in a flat spiral shape. They tested various kinds of shapes and consider whether these different shapes of copper tape could produce enough strength of magnetic field based on their scientific models of electromagnetic force.

The following steps (Activities 5 and 6) repeated the Explain, Engineer, and Evaluate stages of the 6E teaching model. The purpose of these activities is to encourage students to explore the relationship between the volume and the structure of flat speakers more in-depth through reflection on scientific and engineering knowledge after engineering flat speakers in Activity 4.

### Activity 5: Explaining the factors that affect speaker volume

The fifth activity is the Explain stage of the 6E framework. After students gain an understanding of the basic scientific and engineering knowledge of flat speakers in Activities 3 and 4, the instructor leaded students to consider the factors that influence speaker volume according to what they have learned from the scientific model of electromagnetic force. In this activity, students predicted the factors affecting the strength of an electromagnet as well as the interaction between the electromagnet and the magnet in a speaker.

To encourage students to use the scientific model of electromagnetic force in enhancing their products, the instructor first proposed the following question: How can the magnetic field of a long, straight, current-carrying wire be amplified? After group discussion, the instructor prompted students to summarize three main methods: (1) increasing the current in the long, straight, current-carrying wire; (2) tying together several long, straight, current-carrying wires; (3) bending the long, straight, current-carrying wire into a circle.

Then the instructor asked the following: If there is only one current-carrying coil placed with a magnet in the center of the speaker, but the sound is too low after the experiment, how can it be improved? Through group discussion and presentations, students were encouraged to contemplate the relationship between volume and the magnetic force between coils and magnets. Finally, the instructor helped students to postulate which factors that might influence the volume, such as radius of the current-carrying coil, the number of coils, the amount of current flowing, or the strength of magnets.

### Activity 6: Discussing and testing the factors affecting speaker volume through experimentation

The sixth activity comprises the Engineer and Evaluate stages of the 6E framework. First, students were asked to analyze the flat speaker designed in Activity 3 and discuss how they might increase the volume of the flat speaker significantly if they could only change one variable according to the scientific model of electromagnetic force. Then they were instructed to design and conduct an experiment to examine whether the factor they had proposed would influence the volume of their flat speaker by inspecting data concerning the relationship between the changed variable and the volume of the flat speaker. Finally, each group presented and explained their findings to the entire class and examined whether their findings were consistent with their predictions according to the scientific model of electromagnetic force.

### Activity 7: Designing a holiday card with flat speakers with maximum sound volume

Activity 7 comprises the Enrich and Evaluate stages of the 6E framework, which enable students to apply what they have learned to new contexts and assess whether they have applied the principles they have learned in class to design their products. The instructor asked students to design holiday cards for students to apply what they have learned to new applications and utilize their artistic creativity. Then students were asked to examine their own designs according to what they have learned about scientific models and engineering knowledge to produce the maximum volume. An example of a holiday card that was tested is presented in Fig. 3. In the following example, students place several magnets in the center of a spiral-shaped Christmas tree with conductive wires.

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## Declarations

**Conflict of Interest** The authors declare no conflict of interest.

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