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Theorizing STEM Education in the 21st Century

Edited by Kehdinga George Fomunyam

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Meet the editor

Dr Kehdinga started his career as an English Language and Literature teacher in the College of Hopes Arts and Science. After joining the University of KwaZulu-Natal (South Africa), he was appointed a Lecturer in the School of Education, where he taught both undergraduate and postgraduate courses. In 2016 he moved to the Higher Education Training and Development Unit within the same university where he focused on training Masters and PhD students on research skills and later joined the Durban University of Technology as a Research Fellow. He currently works for Mangosuthu University of Technology. He has published several scientific papers on STEM education, curriculum studies, and teaching and learning amongst others. He has supervised more than 22 posgraduate students to completion and has published more than 35 peer-reviewed research articles.

Contents

Preface

Introduction

Significant socio-economic transitions are characterised by a rise in change when, from one generation to the next, people work and live differently than they used to and daily life becomes radically different [1]. These transitions are induced by different inventions, leading to major changes in how people live and relate with one another. The first industrial revolution recorded the introduction of the steam engine, which transformed industries, while the second revolution was associated with the use of electricity to operate new technologies for manufacturing. This era was based on combustion engines and the development of transport, communications, and high-tech industries. This was followed by the third revolution, which saw a shift from a society based on conventional fossil fuel to one based on renewable energy. This revolution is widely known to have been inspired by information technology. Since the beginning of the 21st century, the fourth industrial revolution has been in progress and it presents the possibilities of unprecedented inventions and emerging breakthroughs in technology [2–4].

Widely known as the knowledge age, the 21st century is an age where growth and progress is a function of knowledge and ideas. New patterns of work have been developed and as a result, new kinds of workers with new and different skills are required. According to Khalil and Osman ([5], p.1), "the shift in this current world economy from a manufacturing-based to a knowledge-based economy, scientific innovation, augmented globalisation and advances in communication and information technology (ICT) have changed the job market in this modernised era". This implies that this century is focused on innovations, which is largely driven by advances in Science, Technology, Engineering, and Mathematics (STEM) fields. The generation of innovation in science and technology has become key in the development in this era thereby driving the need for professionals in the fields of STEM. Foundational efforts are being made to prepare students to meet emerging 21st century realities and STEM education has been identified as a priority as it is at the heart of our fast-moving technology-driven world [3]. This preface seeks to expose the need for STEM education in our contemporary society while exploring the possibilities and opportunities that abound in its application in handling real-life situations.

Stem and stem education in the 21st century

Advances in the disciplines of STEM drive innovation and this explains the rationale behind the prioritization of these fields by different societies in this century. These are fields that improve human understanding of the physical environment, support research, and experimentation, in order to gain knowledge and skills needed for the real world. These fields are individually significant and can be taught in isolation, but when collectively applied, they can deepen understanding and be used to solve real-world problems [6]. STEM education blurs the boundaries amongst these disciplines, presenting an integrated approach to solving problems, using interdisciplinary or cross-disciplinary knowledge and skills. The separation of subjects in education has become less relevant in the 21st century as students are no longer taught along the lines of memorization, but are trained to imbibe 21st century skills, develop 21st century approaches and strategies to solving real-life problems [5].

STEM education is the purposeful integration of STEM disciplines with the objective of expanding students' abilities by supporting technical and scientific education with a strong emphasis on critical and creative-thinking skills [7, 8]. Quality education can only be provided if classes and schools are structured towards 21st century skills and knowledge needed for survival in the current global economy, and this has made the need for STEM education vital to today's society. This is a society projected to be driven by technological innovations such as renewable energy, advanced materials, 3D printing, energy storage, genomics, advanced oil and gas exploration, internet of things (IoT), cloud, advanced robotics, and autonomous vehicles [9]. This implies that the future marketplace will experience a radical change and education systems should adapt and respond to these changes. Learners should be equipped with the skills needed for this future and this involves training them to exercise higher level thinking skills by investigating, creating, debating, and synthesizing knowledge [10].

In highlighting skills crucial to education in the 21st century, Shaer et al. [10] insists that there should be a shift from knowledge content-based education to education that focuses more on knowledge use and synthesis, building useful skills and positive character qualities. Some of these needed 21st century skills are creativity, critical thinking, communication, and collaboration. Popularly called the "4C's", these skills have become important considering the volatility, uncertainty, complexity, and ambiguity that dominates this century and the future [11]. Creativity is the ability to produce new and useful ideas, it is the ability to use imagination to create something valuable. A creative student is one that perceives a situation in a novel way by finding not-so-visible patterns and making connections between intricate facts or phenomena. Such a deep-thinking skill is important for students in the 21st century as they begin to think outside the box, and offer solutions on their own to real life problems (Soo, 2019; [12]).

The best solutions are rarely produced in isolation but mostly through joint efforts. Collaboration skills are therefore vital and STEM education supports the conglomeration of multiple perspectives in problem solving. This fundamental skill supports teamwork and shared responsibilities to achieve shared goals. According to Borrego et al. [13], STEM education encourages students to work together as a team to present innovative designs and ideas. Collaboration involves continuous interaction and as such, effective communication is vital. Communication skills are not usually natural and need to be developed as each task requires participation and expression of ideas ([10, 12]; Soo, 2019).

The possibilities of STEM education do not just involve the development of skills vital for living in the 21st century, it also helps us understand the environment we live in (Wallace-Wells, 2017). For one, new technologies provide solutions to environmental threats that abound in our society. One of these threats is the increasing world population as statistics show that by 2050, the world's population will be about 10 billion as opposed to the population of 7.3 million recorded in 2017. This implies that available resources will become stretched and food may become insufficient due to the loss of arable land [14]. STEM education related knowledge can encourage the development of ground-breaking new sources of food production using technology. The spread of these technologies to agriculture will lead to increased yields, lower costs, and reduce the environmental impacts of these predicted global changes [15–19].

These STEM fields, and those who work in them, are critical engines of innovation and growth as these are areas that will drive global development and advancement. It is important that education systems fully integrate STEM as it is the formula for career certainties in a future workforce that is predicted to be STEM based. The benefits of an adaptable future workforce are quite clear, ranging from industrial and economic growth, to innovations that would benefit the planet, STEM education presents the possibility of a successful, competitive, and progressive global economy.

Education in the 21st century has recorded a paradigm shift from content-based education, to an education based on knowledge use and synthesis, building useful skills such as creativity, critical thinking, communication, and collaborative. This is because STEM education has been tasked to prepare students to thrive in a future that has been predicted to be technologically driven and knowledge based. STEM education presents the possibilities of creating a global knowledge-based economy, grooming a capable global citizenry and innovative leadership that possess the right skills, new ideas, and a high level of creativity to solve real life problems. STEM related knowledge can also encourage the development of ground-breaking technologies to tackle the unavailability of adequate resources, such as food due to increased population and loss of arable lands. Experts have also predicted damaging environmental threats to our society such as global warming and its adverse effects on human life. STEM education will also train experts that will create innovative ideas to help preserve our natural environment. In conclusion, educating today's students in STEM fields is a strategic driver for economic growth and global competitiveness. The future workplace has been predicted to be technologically driven and as such, education should prepare today's students to take over tomorrow's workplaces.

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Section 1

Introduction

Chapter 1

Introductory Chapter: Theorising STEM Education in the Contemporary Society

Kehdinga George Fomunyam

1. Introduction

In their bid to strengthen the fields of science and mathematics, the National Science Foundation (NSF) of the United States Department of Education constituted a government policy that will challenge Americans to become leaders in science, technology, engineering and mathematics. This happened right after the launch of the Russian satellite, Sputnik, into space which charged the spirit of the Americans. Originally called SMET (science, mathematics, engineering and technology), this acronym was changed and reintroduced as STEM in 2001 with the plan to completely reform and renew the educational sector with focus on STEM fields [1]. Science which is the first of the four fields improves the human understanding of the physical world while developing research, experimentation and collaborative skills [2]. Science is based on observation, experiment, measurement and laws and its values include independence of thought, creativity, tentativeness, subjectivity, testability and cultural and social embeddedness [3]. Second is technology, which is the satisfaction of human needs and wants using knowledge and skills needed to interface between science and the real world. It is an orchestration of phenomena, programmed for a useful purpose. Third is engineering which involves solving real-life problems using scientifically designed products and processes. Lastly is mathematics which is packed with skills needed to interpret and analyse information, simplify and solve problems, assess risk, make informed decisions and further understand the world through modelling both abstract and concrete problems. Mathematics is concerned with the study of number, shape, space, quantity and their interrelation [2, 3]. Field-specific definitions like his are static as definitions of STEM transcends disciplinary lines. These disciplines are taught in isolation, but STEM education involves a cross-disciplinary approach thereby somewhat blurring their boundaries [4]. This implies that these fields are integrated and the knowledge and skills from two or more fields can be applied to real-world problems.

STEM education is defined differently by different people and groups and has become top priority for education, business and governments. According to Breiner et al. [5], the NSF defines STEM fields broadly, including not only the common categories of mathematics, natural sciences, engineering, computer and information sciences but also social behavioural sciences such as psychology, economics, sociology and political science. For [1], STEM education is a teaching field based on constructivism and constructionism, while Caparo [6] defines it as a teaching composite of any two or more fields of science, technology, engineering and mathematics, which may occur as a result of duplicity of real-life and problem-based learning.

STEM is commonly used to reference a set of educational and occupational fields related to science. It is the purposeful integration of the science, technology, engineering and mathematics discipline in solving real-world situations [7].

These disciplines can be taught and applied either in a traditional and discipline specific manner, or through a multidisciplinary, interconnected and integrative approach [2]. Mitts [8] and Bruce-Davis et al. [9] support the critical analysis of STEM education using two approaches. For them, the first approach is the integrative approach which is a composite of major disciplines integrated into one. The second is the multidisciplinary approach, an approach that integrates knowledge from several disciplines. These approaches use problem-based learning, project-based learning or inquiry-based learning as strategies to produce results. Both approaches are outcome-focused and aim to solve real-world challenges [2]. STEM education and training establishes relationships between the four disciplines with the objective of expanding peoples' abilities by supporting technical and scientific education with a strong emphasis on critical and creative thinking. These are skills vital for existence in today's world which is at the brink of a technological revolution.

2. The era of the fourth industrial revolution

In the past, several revolutions have defined the world and according to the World Economic Forum, the fourth industrial revolution is here already [10]. The first industrial revolution saw the introduction of the steam engine which transformed industries; it was a revolution that changed most agrarian societies to industrialised ones as the world discovered and began to rely on steam power and machine tools [11]. The second industrial revolution was based on combustion engines [12] and associated with new technologies for manufacturing that used electricity. This era witnessed the transition to electricity, the development of transport, communications and the development of high-tech industries. It was a period of growth for pre-existing industries as science, technology, engineering and mathematics (STEM) were brought into factories leading to advancements in education [11]. The focus of the third industrial revolution was on the paradigm shift from a society based on conventional fossil fuel to a society based on renewable or alternative energy. This was a revolution inspired by information technology and linked to web-based interconnectivity and computerisation [12]. Often referred to as the digital revolution, it involved the transition to telecommunication technologies, automation of production and rapid development of services [13].

Currently, the world is on the brink of another revolution that will alter the way we live, work and relate with one another. Lee et al. [13] state that the fourth industrial revolution has been in progress since the beginning of the twenty-first century and is a concept triggered and based on recent diverse technologies. This revolution is characterised by the convergence of breakthrough technologies such as advanced robotics, artificial intelligence, virtual reality, wearables and additive manufacturing that will transform production processes and business models across all industries [14]. Usually referred to as 4IR, the fourth industrial revolution has continued to gain momentum, influencing every sphere of human life. According to [12], twelve disruptive technologies reshaping the world in the era of 4IR are renewable energy, advanced materials, 3D printing, energy storage, genomics, advanced oil and gas exploration, Internet of things (IoT), cloud, advanced robotics and autonomous vehicles. This is a revolution characterised by a fusion of technologies, blurring the lines between the physical, digital and biological spheres.

3. Projections of 4IR

The World Economic Forum in 2015 defined a set of tipping points by which the technologies of the fourth industrial revolution will become widespread, such that it will create significant societal change. These points are the proliferation of the fourth industrial revolution technologies to levels where they make remarkable impacts on our lives and require shifts in education and employment. A survey of 800 high-tech experts and executives determined a series of dates by which these tipping points would be reached. They state that by 2025, implantable cell phones will exist. 2023 will see 80% of people in the world digitally present and 10% of reading glasses connected to the Internet. By 2022, 10% of people will be wearing internet-connected clothes, and 90% of the world population will have access to the Internet by 2024. The year 2023 will see 90% of the world population using smart phones, and over 50% of Internet traffic will be directed to homes and appliances by 2024 [10]. 3D printed cars will exist by 2022, and by 2024, there will be transplants of 3D printed organs such as the liver. Many other predictions suggest extensive integration of artificial intelligence in the twenty-first-century workforce. This will lead to the loss of 75 million jobs by 2022, but 133 million new jobs will be created by new technologies for people trained to work with machines and data [14]. In fact, 65% of children entering school today will eventually work at jobs that do not currently exist.

Statistics show that as of 1950, the world population was 2.5 billion, and this increases to 5.3 billion by 1990 and 7.3 billion by 2017. It has been projected that by 2050, the world population will be 10 billion. Increasing population coupled with the loss of arable land, as a result of global climate change, will require an increase in food production efficiency of more than 50% by 2050, thereby placing an imperative on industry 4.0 technologies to develop groundbreaking new sources of food production. Environmental threats arising from a buildup of Co_2 as well as other greenhouse gases are also expected, and according to [12], there will be an increase in temperature to more than 10°C. Global warming could make the earth uninhabitable in which case, the result would be widespread crop failures, subjecting large fractions of the world's populations to heat exhaustion and potential death. The predicted rise in temperature will lead to a great reduction in agricultural productivity by as much as 15% for every degree of warming. New technologies in this era could attenuate global warming by absorbing excess carbon dioxide using both bioengineered organisms and new materials within buildings.

According to Professor Klaus Schwab at the World Economic Forum, this "transformation will be unlike anything humankind has experienced before. We do not yet know just how it will unfold, but one thing is clear: the response to it must be integrated and comprehensive, involving stakeholders of the global polity, from the public and private sectors, to academic and civil society" ([10], p. 5). Educational responses to 4IR would be to retool STEM institutions and curriculum to provide new departments and science programmes in new interdisciplinary fields in a bid to provide more efficiently trained workers to help advance and accelerate the development of ever-more sophisticated artificial intelligence, biotechnology and nanotechnology. The education system is adopting these new changes, and STEM education has been identified as a new approach to be used in the education system globally.

4. STEM education responses for the contemporary society

As stated by [16], the implications of 4IR for education is twofolds with the first being required research and interventions from scholars and scientists on making intelligence not just an industrial tool but also useful in the direct service to society. The second implication affects the teaching and learning process including the curricula. Considering the dynamic changes in society, education has to change, and a revolution in teaching and learning methodologies is necessary so as to adopt a type of learning outcome based on competencies, blending academic and vocational education to answer the market need. Teaching and learning should now reflect edutech services, lifelong learning pathways, digital fluency and STEM skills [15].

Today's educational system is tasked with preparing this generation and the next to thrive in the face of these projections that would change the world, and STEM education is the answer. A relationship between STEM education and 4IR should be fostered so as to produce scholars with twenty-first-century skills that can solve real-life problems such as collaboration skills, communication skills, critical thinking skills, problem-solving skills and all-round creativity. To achieve this, STEM education must be fully integrated into the school curriculum such that regardless of the course of study, each individual is prepared for the future workplace. Exponential growth and rapid change give the curriculum an imperative to update its content to match the rapid tempo of scientific and technological advances. The jobs of tomorrow are rooted in STEM; therefore integrated instruction should focus on STEM fields so as to create critical thinkers and empower the next generation of innovators [16].

The foundations for STEM education should be introduced to children early on so as to pique their interest and get them curious. This can be achieved through hands-on multisensory and creative experiences as it helps children develop curiosity, critical thinking and problem-solving capacities. In the long run, they become interested in STEM fields and are more likely to undertake one of these fields as a major. This era also demands that students are trained to be entrepreneurial so that their thoughts will be diversified, to not just technical education. Developing an enquiring mindset and attitude will ensure that they function adequately in the dynamic and flexible workplace of today [15–17].

All these point to the criticalness of STEM education in the current dispensation and attest to the need of this volume. This book is therefore a timely addition to the scholarship on STEM education and provides valuable insight in the teaching and learning of science, technology, engineering and mathematics. It also provides insight to the scholarship in these fields as they relate to each other and the broader STEM field.

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Section 2

Theorising the Interdisciplinary STEM

Chapter 2

Implementation and Didactic Validation of STEM Experiences in Primary Education: Analysis of the Cognitive and Affective Dimension

Guadalupe Martínez-Borreguero, Milagros Mateos-Núñez and Francisco Luis Naranjo-Correa

Abstract

Several studies highlight the need to improve STEM competencies from an early age, where the first attitudes and vocations toward these subjects begin to be forged. This research pursued two general objectives: First, to analyze the cognitive and affective dimension of primary education students in relation to STEM content, using a sample of 801 students. Second, to implement and validate STEM experiences as didactic strategies that improve the teaching/learning of these areas in students aged 10–12, using a sample of 455 students. The design of the research was quasi-experimental with pretest, posttest, control, and experimental groups, analyzing both cognitive and affective variables. The inferential statistical analysis of the obtained data reveals that STEM education promotes a positive evolution in the students both in the learning and emotional variables, existing statistically significant differences compared to a traditional methodology.

Keywords: STEM, primary education, cognitive domain, affective domain

1. Introduction

In recent years, there has been a need to reorganize science and technology education programs based on the new paradigms of society. The reason for considering this area in particular is the growing need for professionals specialized in this type of education in the market, since the proportion of students who choose STEM (science, technology, engineering, and mathematics) areas in higher education is not enough [1–3]. Children's learning is strongly influenced by the contexts in which the teaching process takes place in schools [4]. Previous research has suggested that offering more rigorous math and science courses can foster higher level skills and confidence within these subjects [5, 6] and improve students' chances of pursuing STEM careers [7].

Paradoxically, while most students enjoy learning science at an early age [8], many lose interest in high school because mathematics and science seem irrelevant to their personal goals and they are not aware of the usefulness of this knowledge in everyday life [9]. As students progress academically, they begin to consider that science subjects are complex and boring [10]. Other authors [11] add that students show low motivation and mood in learning activities related to STEM areas. This can be linked to the methodologies and teaching strategies used in science classrooms [12]. Similarly, reports from the Organisation for Economic Cooperation and Development [1] state that young people are not able to solve scientific problems in creative and innovative ways and experience difficulties in addressing activities and challenges associated with the areas of science and technology. This may be associated with a lack of motivation for learning [13] or even with the emotions the students experience toward learning science [14]. With respect to emotional domain, it should be noted that several studies relate it both to cognitive domain and to the concept of self-efficacy presented by the students [15]. According to some authors [16], students' perception of their self-efficacy in scientific-technological subjects predicts their performance in these areas. Beliefs of academic self-efficacy shape students' school and professional aspirations [17]. That is, successful performance improves the perception of self-efficacy and the expectation of positive results, thus strengthening the interests and goals to be achieved [18, 19]. Students will show higher rates of self-efficacy if they show concentration, control, happiness, participation, and satisfaction during school work [20, 15]. However, academic and competency performance is lower as a negative view of addressing their learning process is higher [21].

Although students' interest and positive attitudes in science diminish throughout schooling [22], STEM interdisciplinary programs can provide the time and space needed to address this decline in scientific vocations and commitment [23]. Specifically, various studies [24] suggest that STEM competencies should be encouraged from an early age by using innovative teaching strategies that encourage the internalization of content so that it is maintained over the long term. In addition, it is more feasible to implement an integrated curriculum of these subjects in primary education because students spend most of their school time with their tutor teacher. Thus, an interdisciplinary and integrated treatment of STEM competencies would not negatively affect the educational process at these levels [25].

STEM education requires alternative didactic strategies to traditional teaching aimed at promoting a more valid and useful school science that involves students in improving their STEM skills [26]. Thus, for example, scientific models and theories will become relevant for students if they are given opportunities to test their usefulness and explanatory potential [27, 28]. The inclusion of STEM experiences in the curriculum at the primary education stage can improve the understanding of the youngest toward the diverse scientific-technological roles of society, as well as improve involvement, motivation, and the search for solutions to real problems by contextualizing mathematics, technology, engineering, and science contents [29].

Schools that offer STEM-focused programs have become the center of several policy initiatives and research projects [30]. Results from some studies [31] indicate that students' intention to specialize in one of the STEM areas or the likelihood that students will choose a STEM major is positively correlated with attendance at schools with STEM educational programs. Many educators believe that schools with a STEM approach will promote the preparation of well-informed citizens who have access to and appreciation of the ideas and tools of science and engineering [32]. In addition, schools that focus on science, technology, and innovation are also an enabling strategy for closing racial and gender gaps in learning opportunities in these fields [33]. In addition, these educational programs offer students the opportunity to have more information about STEM disciplines and greater academic and employment opportunities [31].

However, the challenges associated with change must be supported by management, continuous workforce development, and educational programs that focus on the specific needs of teachers in transition to a new form of teaching [34]. Teachers who do not acquire continuous training or those who do not have time to carefully develop an integrated curriculum may adopt an unstructured curriculum rather than a truly integrated approach [35]. Extracurricular STEM schools and programs must address the challenge from various sectors, not only by trying to improve actual achievement but also by helping students develop cognitive skills and greater confidence in their ability to learn and do science [9]. To help all students believe they can understand STEM areas, schools and extracurricular programs must address the challenge from various perspectives, helping students develop metacognition skills and greater confidence in their theoretical and procedural ability [36]. Based on this background, the research presented here is intended to analyze cognitive and affective aspects toward STEM areas in students aged 8–12.

2. Methodology

2.1 Research design

This research is based on two parallel studies focused on STEM education in the function of diverse variables related to cognitive, affective, and competency aspects.

Study 1 has been oriented to analyze the cognitive and affective dimensions that primary education students present toward STEM areas, following an exploratory research design with a mixed analysis of the obtained data.

Study 2 has been aimed at validating the implementation of STEM workshops in the primary education classroom, following a quasi-experimental research design with pretest, posttest, control, and experimental groups, analyzing both cognitive and affective variables.

2.2 Objectives

The research carried out has pursued two general objectives based on the two studies proposed:

General objective 1 (study 1): to analyze the cognitive, affective, and competency dimensions of primary school students in relation to STEM areas.

General objective 2 (study 2): to implement and validate STEM workshops as active didactic strategies that improve the teaching/learning of these areas in primary school students.

2.3 Hypothesis

The general objectives have served as a reference for formulating the following research hypotheses:

Hypothesis 1 (H1): elementary students have a low level of knowledge in STEM areas.

Hypothesis 2 (H2): there are differences in the level of knowledge in STEM areas of the primary students depending on the variable academic level.

Hypothesis 3 (H3): there are no statistically significant differences in the level of knowledge in STEM areas as a function of the gender variable.

Hypothesis 4 (H4): primary school students show a favorable attitude toward STEM subjects and their learning.

Hypothesis 5 (H5): elementary students have low levels of proficiency in STEM areas.
Hypothesis 6 (H6): there are no statistically significant differences in competency values with respect to the gender variable.
Hypothesis 7 (H7): the implementation of STEM workshops in the primary classroom as didactic strategies produces a cognitive and emotional evolution in the students.
Hypothesis 8 (H8): there are statistically significant differences in cognitive and affective variables between the students who use a traditional methodology and those who use a methodology based on the implementation of STEM workshops.
Hypotheses 1–6 are checked in Study 1 and hypotheses 7 and 8 in Study 2.

2.4 Sample

The sample was selected through a random process, involving 1256 primary school students. Since the two general objectives were set according to the two studies, the sample participating in the research was divided into two subsamples.

Subsample 1 consisted of 801 pupils aged between 8 and 12 from different schools. This group was used for Study 1 with an exploratory character on cognitive, affective, and competence variables.

Subsample 2 consisted of 455 students aged 10–12 from different schools. The students in each school were divided into two homogeneous groups, control and experimental according to the theme of the different STEM workshops implemented. This group was used for Study 2 with a quasi-experimental purpose to validate the didactic relevance of the implementation of the STEM workshops. The STEM contents worked on in the control groups and experimental groups have been the same and were selected from the education curriculum. The control groups (CG) have followed a methodology based on a more traditional teaching of the selected STEM contents, using as resources the textbooks and their specific worksheets. However, the experimental groups (EG) have followed a teaching methodology based on STEM workshops. This type of resources allows interdisciplinary work on diverse scientific, technological, and mathematical contents, as indicated in previous studies [37]. The workshops have been designed in such a way that they can be carried out in 2 or 3 classroom sessions. They consist of making a model with easily acquired or recycled materials to facilitate their reproduction in informal contexts. The construction of the model makes it possible to work on different contents of the STEM areas involved, which are selected from the primary education curriculum. In addition, they are accompanied by a video, a didactic guide, and an observation sheet for the students, in order to focus their attention on the contents worked on.

2.5 Measuring instrument

Different measuring instruments have been designed and implemented according to the research objectives.

For Study 1 carried out with subsample 1, a questionnaire was designed divided into two sections (Questionnaire 1). The first section evaluated affective and competency aspects and consisted of 21 questions with 4 answer options. Some of the questions were aimed at verifying the degree of affectivity and appreciation of the student toward science in different contexts. Other questions asked were intended to diagnose the level of competence, capacity, or self-efficacy of the student participant in different real situations related to STEM tasks. As an initial diagnosis, the second

Example of questions related to the affective and competence dimension	
4. Do you like to learn science by doing experiments and hands-on tasks? a. I love it b. I'm good at it c. I'm bad at it d. It bores me	7. Have you ever disassembled a toy to see what it's like inside? a. Yes, I wanted to see how it worked b. Yes, but it broke down c. No, but I'd like to do it d. Never

Table 1.
Example of questions related to the affective and competence dimension.

Example of questions related to the cognitive dimension	
2. Julia and Henry are making a model with an electric circuit for school. What materials do they need for the circuit to work? a. A battery, a light bulb, a switch, and the conductor wires b. A wooden stand, a battery, and insulating cables c. A battery, a light bulb, a conductor cable, and a wooden stand d. Two batteries and a switch	9. Laura's blender receives electricity from the grid by plugging it into an outlet. But into what do you think the mixer transforms the electricity it receives? a. In motion so that the ingredients are well mixed b. In heat so that the ingredients remain in a liquid state c. In sound, that's why it makes so much noise when we use it

Table 2.
Example of questions related to the cognitive dimension.

section of the questionnaire had the purpose of assessing the level of STEM knowledge of the students by means of 10 multiple choice questions about theoretical contents or situations of application of the contents. The content of these 10 questions is based on the education curriculum of the primary stage. **Table 1** shows some of the affective and competence questions of the first section of the questionnaire.

Table 2 shows some questions from the second section aimed at assessing the level of STEM knowledge.

For Study 2 on the validation and implementation of STEM workshops with subsample 2, various questionnaires were designed according to the workshop topic. Specifically, for each workshop, one was developed as a pretest to evaluate the initial level of knowledge of the participating sample and another as a posttest to check whether student learning improved after the explanation of the contents by means of the two didactic methodologies used: that of the control group and that of the experimental group. The questions used in these questionnaires were based on the questions in the textbooks of the different publishers used by the students in the classroom. By way of example, one of the questions from workshop 3 is specified. "*When approaching a traffic light, a cyclist stops pedaling. For a while, however, the bicycle continues to move. What causes the bicycle to stop after a certain time*?"

3. Results

3.1 Results of Study 1: analysis of the cognitive, affective, and competence dimensions of primary school students in relation to STEM areas

First, a descriptive analysis of the cognitive dimension is presented and then the inferential analysis is detailed in order to test the proposed research hypotheses. Next, the results related to the affective dimension and finally those related to the competence dimension are represented.

3.1.1 Cognitive dimension analysis

The descriptive statistics obtained by subsample 1 (n = 801 students) in the knowledge questionnaire are presented. Primary school students score an average of 5.38 points out of 10, with a standard deviation of 1.72. Although the score obtained suggests that students show knowledge about STEM content, the analysis by questions reveals that the level of knowledge is worse when it comes to answering purely theoretical questions. However, students scored better on content-related questions about real situations, coinciding with other studies [38, 9].

Table 3 shows the descriptive statistics obtained in the STEM level of knowledge of primary school students according to the variable academic level.

As can be seen in **Table 3**, third-grade students score an average of 4.82 points out of 10; fourth-grade students score 5.46 points; fifth-grade students average 5.44 points; and sixth-grade students average 5.74 points. Regardless of the academic year, the cognitive level of the students is not very high, although it is true that there is a cognitive improvement with academic progress. However, the results obtained allow us to accept Hypothesis 1 "*Elementary students have a low level of knowledge in STEM areas.*" In order to verify the existence of statistically significant differences depending on the variable academic level, an ANOVA statistical test of one factor with Tukey's post hoc has been carried out. The results obtained are shown in **Tables 4** and **5**.

The data presented in **Table 4** show the existence of statistically significant differences in the STEM cognitive domain between academic courses obtaining a significance of 0.001. The analysis with Tukey's post hoc shown in **Table 5** indicates that these differences in the variable level of knowledge appear among third vs. fourth graders (Sig. = 0.005) and among third graders vs. sixth graders (Sig. = 0.000), favoring the average score to students in the upper grades in both cases. It seems evident that the STEM contents are dealt with in greater depth in the more advanced courses; however, it is necessary to pay attention to the didactic strategies used to avoid forgetting in the higher courses [39]. On the other hand, the data presented above make it possible to accept Hypothesis 2 "*There are differences in the level of knowledge in STEM areas of the primary students depending on the variable academic level.*"

School year	Mean	Std. deviation	Std. error of the mean
3rd PE	4.82	1.59	0.13
4th PE	5.46	1.71	0.11
5th PE	5.44	1.50	0.18
6th PE	5.74	1.84	0.15

Table 3.
Descriptive statistics (academic level).

ANOVA		Sum of squares	Df	Mean square	F	Sig.
Average score	Between groups	61.775	3	20.592	7.111	0.001*
	Within groups	1595.479	551	2.896		
	Total	1657.254	554			

**Sig. < 0.05.*

Table 4.
One-factor ANOVA test (academic level).

(I) School year	(J) School year	Mean difference (I-J)	Std. error	Sig.	95% confidence interval	
					Lower bound	Upper bound
3rd PE	4th PE	−0.638	0.189	0.005*	−1.126	−0.149
	6th PE	−0.917	0.203	0.000*	−1.442	−0.392

Sig. < 0.05.

Table 5.
Tukey's HSD post hoc test (academic level).

	Mean	Std. deviation	Std. error of the mean
Men	5.47	1.74	0.10
Women	5.32	1.69	0.10

Table 6.
Descriptive statistics (gender).

On the other hand, it is intended to analyze the influence of gender on the variable level of knowledge due to the numerous existing stereotypes in relation to the subject. Specifically, some authors [40] point out that girls outnumber boys when it comes to participating in class and doing homework, but boys do better on physics tests. Other studies [41] indicate that gender differences can be reduced with a value affirming intervention. On the other hand, [42] indicate that the gender gap in STEM disciplines goes beyond the limited representation of women since women actually score lower on exams and on standardized tests on scientific concepts. Other authors [43] also agree that women show a greater preference for studies related to the health sector (nursing, veterinary, or microbiology) and men choose careers such as architecture, engineering, physics, or computer science. **Table 6** shows the descriptive statistics according to the gender variable.

As can be seen in **Table 6**, boys score an average of 5.47 points with a standard deviation of 1.74. On the other hand, girls achieve a score of 5.32 points with a standard deviation of 1.69 points. These results seem to indicate that in the exploratory study carried out with subsample 1 (primary school students) there is STEM knowledge equity regardless of gender. Nevertheless, it was thought convenient to validate this assertion by means of an inferential analysis. **Table 7** shows the Student's t-test carried out.

As can be seen in **Table 7**, the value of the significance obtained was Sig. = 0.305, so we can accept Hypothesis 3 "*There are no statistically significant differences in the level of knowledge in STEM areas as a function of the gender variable.*"

	T	Df	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
						Lower	Upper
Mean	1.026	548	0.305*	0.150	0.146	−0.137	0.438

Sig. < 0.05.

Table 7.
Student's t-test (variable: gender).

3.1.2 Analysis of the affective dimension

The results obtained when analyzing the affective dimension in relation to STEM areas in formal and informal contexts are shown. **Tables 8–12** show the percentages obtained in some of the questions asked. The answers obtained in the different options are specified.

Tables 8–12 show that elementary students show a positive attitude toward learning STEM areas in different contexts. The majority of participants show a favorable attitude in the statements within the educational environment (**Table 8**) and show a preference for experimental methodologies (**Table 9**). This fact is verified again when analyzing STEM learning issues in experimental or practical environments. Specifically, **Table 10** confirms the preference for practical teaching strategies. On the contrary, there is a decrease in the percentage of students who select the positive items in matters in which leisure is related to STEM areas. Generally, the percentages reached are mostly positive as can be seen in **Tables 11** and **12**, but negative attitudes increase in cases such as the choice of toys or television channel. Taking into account the results obtained in the affective-attitudinal dimension, we can accept Hypothesis 4 "*Primary school students show a favorable attitude toward STEM subjects and their learning.*"

2. Do you like the activities you do in science classes?	I love them (48.0%)	I'm good at them (39.4%)	I'm bad at them (3.3%)	They bore me (8.9%)

Table 8.
Percent of students who select different items from Statement 2.

4. Do you like to learn science by doing experiments?	I love it (82.9%)	I'm good at it (11.0%)	I'm bad at it (3.7%)	It bores me (2.0%)

Table 9.
Percent of students who select different items from Statement 4.

6. Would you like to learn how to create robots?	I'd love to (70.7%)	Yes, I'd be good at it (11.0%)	No, I would not be good at it (11.8%)	No, I'd be bored (6.1%)

Table 10.
Percent of students who select different items from Statement 6.

17. Would you ask Santa Claus to bring you science games?	Yes, I love them (43.9%)	Maybe, they'll be entertaining (34.1%)	No, I would not know how to play (3.3%)	I prefer more fun games (15.0%)

Table 11.
Percent of students who select different items from Statement 17.

19. Do you like math puzzle books?	Yes, I love them (46.3%)	Yes, but I do not know how to solve them; I'd like to learn (29.3%)	No, I do not know how to solve them and they are useless (3.3%)	I'm not interested in them at all (19.1%)

Table 12.
Percent of students who select different items from Statement 19.

3.1.3 Analysis of the competence dimension

This section presents the results related to the level of competence and self-efficacy of primary school students in the resolution of different scientific-technological situations. **Tables 13–16** show some of the results of this section.

Tables 13–16 show that, in general terms, subjects are considered competent when carrying out STEM activities, because in the items of positive self-efficacy percentages prevail. Specifically, Statement 7 (**Table 13**) is where the lowest levels of self-efficacy are obtained. On the contrary, in Statement 11 (**Table 14**) a higher percentage of students is observed in the positive items, especially in the item referring to positive self-efficacy with 45.9% of students, although it is true that 35% of students would request some help for its execution. The same occurs in Statement 14 (**Table 15**) and in Statement 21 (**Table 16**). In both cases, the majority of students show high levels of self-efficacy, with 51.6% of students indicating that they feel qualified in Statement 14 (**Table 15**) and up to 80.5% of students considering themselves capable of resolving without problems the task proposed in item 21 (**Table 16**). Based on these results, with respect to Hypothesis 5 (*Elementary students have low levels of proficiency in STEM areas*), it should be noted that it is partially accepted since the level of self-efficacy of the participating sample varies depending on the context of the task to be performed. On the other hand, it was decided to evaluate the results of the self-efficacy variable according to gender and it was obtained that there are no statistically significant differences (Sig. > 0.05) in this variable, allowing it to accept Hypothesis 6 "*There are no statistically significant differences in competency values with respect to the gender variable.*"

7. Have you ever disassembled a toy to see what it's like inside?	Yes, I wanted to see how it worked (26.4%)	Yes, but it broke down (12.6%)	No, but I'd like to do it (29.7%)	Never (30.9%)

Table 13.
Percent of students who select different items from Statement 7.

11. If you had the necessary materials, would you be able to build a swing on a tree?	Yes, no problem (45.9%)	Yes, but with some help (35.0%)	No, but I'd try (17.5%)	I would not be able to build it (1.6%)

Table 14.
Percent of students who select different items from Statement 11.

14. Have you ever tried to repair a broken toy or device?	Yes, and I've fixed it (51.6%)	Yes, but I did not fix it (37.4%)	No, because I do not think I can fix it (5.3%)	No, because it bores me (3.7%)

Table 15.
Percent of students who select different items from Statement 14.

21. Do you like to set up a domino effect?	Yes, and the longer the better (80.5%)	Yes, but one that does not take long (10.6%)	I would not be able to finish it (2.4%)	No, I find it very boring (4.1%)

Table 16.
Percent of students who select different items from Statement 21.

3.2 Results of Study 2: implementation and validation of STEM workshops as active didactic strategies that improve the teaching/learning of these areas in primary school students

Figure 1 shows the results obtained in the pretest of the control and experimental groups that make up subsample 2.

The results shown in **Figure 1** show the existence of a low level of knowledge on the part of primary school pupils before carrying out the different didactic interventions, both in the control groups and in the experimental groups of the different schools. This is due to the fact that it was decided that contents that were not previously studied by the students of the participating groups will be chosen, in order to establish a homogeneous starting point between both. It can be observed (**Figure 1**) that no group obtains a passing grade. Likewise, the inferential analysis carried out revealed that there were no statistically significant differences (Sig. > 0.05) in the mean scores of the control and experimental group and that both groups started with the same level of STEM knowledge and with similar science preconceptions.

Figure 2 shows the results obtained in the posttest of the different groups, revealing a notable cognitive improvement in all cases after the didactic interventions exposed to the control groups and after the STEM workshops carried out in the experimental groups.

As shown in **Figure 2**, it can be verified that all students improve their STEM knowledge level after the didactic interventions, regardless of the type of teaching applied. However, the students in the experimental groups have not only improved their score with respect to the pretest but also obtained higher scores than the students in the control groups. Active strategies are considered the best method for teaching science, promoting research skills in students and helping them internalize new knowledge in the search for answers to previously formulated scientific questions [44]. It seems clear that the experimental group has improved its average score with respect to the pretest and more easily remembered the contents than the control group. However, a Student's t-test was conducted to check for statistically significant differences in mean scores between groups. The results are shown in **Table 17**.

As can be seen in **Table 17**, there is a mean difference of 1.33 points out of 10 in School 1 with a significance of 0.013, favoring the experimental group. In School 2, a mean difference of 1.23 points out of 10 was obtained in favor of the experimental group, also obtaining a significance of 0.043. Likewise, in School 3, a mean

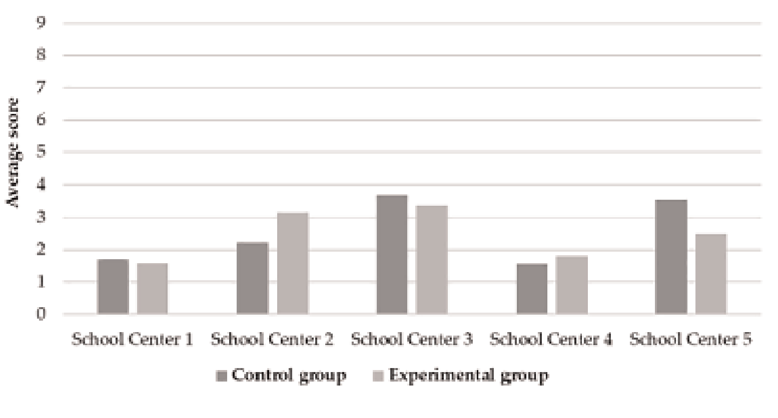

Figure 1.
Pretest results.

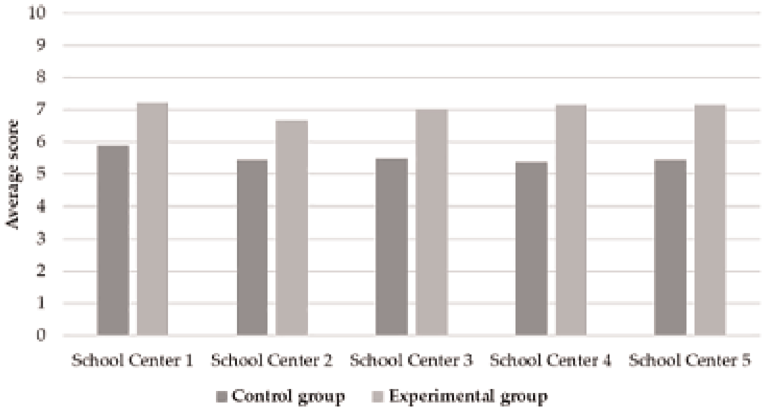

Figure 2.
Posttest results.

Post-test	t	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
					Lower	Upper
School center 1	−2.586	0.013*	−1.333	0.515	−2.375	−0.291
School center 2	−2.087	0.043*	−1.238	0.593	−2.437	−0.039
School center 3	−3.428	0.001*	−1.560	0.455	−2.474	−0.647
School center 4	−3.940	0.000*	−1.771	0.449	−2.678	−0.864
School center 5	5.756	0.000*	−2.083	0.361	1.356	2.810

Sig. < 0.05.

Table 17.
Student's t-test (control group vs. experimental group).

difference of 1.56 points was obtained in favor of the experimental group, leading to the existence of statistically significant differences (Sig. = 0.001) between groups. In School 4, there is a mean difference of 1.77 points out of 10 and there is a significance of 0.013 in favor of the experimental group. Finally, in School 5, there is a mean difference of 2.08 points out of 10 and a significance of <0.0001 in favor of the experimental group. The results reveal that there are statistically significant differences between the control and experimental groups in favor of the latter and consequently validate the effectiveness of STEM workshops in learning. The proposed STEM workshops have made it possible to address competence skills in the classroom and to use relevant everyday contexts of real life to promote STEM motivation and learning in a meaningful and contextualized way [45].

With respect to the emotional variable, the degree of manifestation of positive and negative emotions expressed by the experimental groups before and after the explanation of the contents through the STEM workshops is shown in **Figure 3** by way of example. It can be observed that after the realization of the STEM workshops the primary students significantly increase (Sig. < 0.05) their positive emotions (fun, interest, joy, or confidence), decreasing the degree of manifestation of negative emotions such as stress, desperation, worry, or sadness.

The results obtained after the implementation of the STEM workshops shown above allow us to accept Hypothesis 7 "*The implementation of STEM workshops in the primary classroom as didactic strategies produces a cognitive and emotional evolution in*

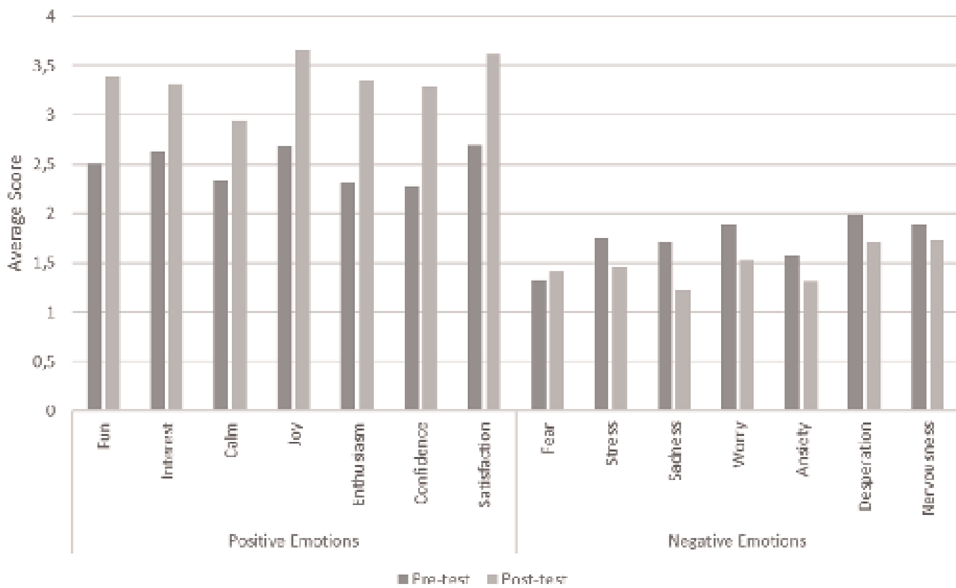

Figure 3.
Emotional results obtained by the experimental groups.

the students" and Hypothesis 8 "*There are statistically significant differences in cognitive and affective variables between the students who use a traditional methodology and those who use a methodology based on the implementation of STEM workshops.*"

4. Discussion

The results show a favorable trend toward STEM areas among primary school students. Although recent studies by some authors [22] indicate that there is a significant decline in students' attitudes toward school science throughout primary school, this research argues that primary school students show great interest and enthusiasm for science subjects and their learning, coinciding with other work [46], and the students are generally competent in this field. However, the results on cognitive domain tend to make us reflect on whether the chosen teaching methods are the most suitable for meaningful STEM learning, since there is a certain lack of knowledge on the subject, thus coinciding with previous scientific literature [47, 48]. It is important to know to what extent students, once they have completed their schooling, are adequately prepared to apply knowledge in understanding important issues and in solving significant problems [49], since inadequate scientific training from an early age will have a negative impact on future learning and attitudes.

In addition, the results show that hands-on, experimental activity generates motivation and a desire to learn [50]. Along these lines, it would be convenient to adapt the teaching style of the teachers to the preferences and way of learning of the students in order to improve and facilitate the teaching-learning process [51]. Furthermore, we consider that in order to promote scientific and technological literacy in the long term, it will be decisive for the educational system to promote practical activities, projects, and competency workshops [24]. The scores obtained by the experimental groups show that the experiences made in the workshops help to eliminate firmly rooted misconceptions in the students and allow the acquisition of contents that are difficult to understand when the phenomenon studied is observed directly [24]. On the contrary, the results of the control groups show that textbooks and traditional strategies only develop scientific knowledge and are governed by the internal logic of science, without asking what science is, how it develops, or what benefits it brings to society [52]. It should also be noted that despite existing stereotypes about gender inequality problems and claims that science and technology are mainly male-dominated fields [41], the results of this study with respect to cognitive and self-efficacy domains show that there are no gender differences in STEM areas at the elementary stage of education.

It is therefore considered necessary to create and study new resources and methodologies that facilitate and motivate the learning of STEM areas and promote thinking strategies for students in the different early stages of their education. The proposed didactic model based on STEM workshops provides an appropriate environment for primary school pupils to learn to be creative, to solve real challenges or problems, and to improve not only STEM competences but also other competences such as collaborative learning, the use of virtual scenarios, the creation of informal learning opportunities, and actively sharing learning with others [53]. Along these lines, we agree with other studies [33, 54] that there is a positive and significant relationship between STEM-integrated learning and students' academic achievements, interests, and aspirations in relation to these areas.

Likewise, these new educational strategies make it possible to acquire higher cognitive levels of science and technology in students of all ages, and more specifically from early ages, where interest in science generates positive emotions and attitudes [8]. From this perspective, the aim of STEM education, rather than replacing spontaneous ideas with scientific ones, is to provide individuals with new explanatory models for interpreting the world and to help them recognize that scientific knowledge is, in many cases, more appropriate than their misconceptions for describing or understanding certain phenomena [55]. The use of experimentation in the classroom will promote a willingness to learn, will make it easier for children to face tasks, and will make it easier for them to achieve objectives, and, in addition, the goals achieved will be much greater [24]. In brief, STEM education involves working in the context of complex phenomena or situations that require students to use knowledge and skills from multiple disciplines to solve real-world problems [26]. With all the above, it is finally concluded that personal factors such as interests, attitudes, and beliefs about self-efficacy will be key aspects to influence the choice of STEM subjects and the professional expectations of students [19].

5. Conclusion

Once the different variables of the study have been analyzed, we can conclude that traditional activities are, in general, boring for the students and do not help their learning to be effective and lasting. On the contrary, the implementation of STEM practical experiences in formal contexts generates a favorable framework to promote the learning of technical and manipulative skills and fosters underdeveloped research skills in primary school students, such as the habit of formulating hypotheses, experimenting, establishing their own conclusions, and being critical, while respecting the conclusions of their peers.

In addition, students seem to understand that learning through hands-on, active learning strategies is enriching, facilitates the task of learning and acquiring knowledge, and is fun, entertaining, and motivating.

The results obtained allow us to highlight the importance of educators using active teaching methodologies that involve a greater role for their pupils. Thus, students realize that there are many ways to present STEM areas, beyond the mere theoretical master class, but without ever losing sight of the scientific rigor.

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Chapter 3

Inverse Modeling Problems in Task Enrichment for STEM Courses

Victor Martinez-Luaces, José Antonio Fernández-Plaza and Luis Rico

Abstract

Problem solving is considered as one of the most important topics in STEM (science, technology, engineering, and mathematics) education, and this is especially relevant when problems require modeling skills in order to be solved. Also, it should be noted that in many branches of science and technology, typical problems are posed in an inverse form. Then, combining both characteristics, the so-called inverse modeling problems deserve to be studied deeply, particularly in their potential for task enrichment. For those reasons, since 2016, a research project was carried out, by using inverse modeling problems to develop prospective teacher's task enrichment skills. The results of this experience that took place in 2017 showed nine different groups of proposals where only few participants were very creative, whereas many others posed trivial problems or simply imitated examples analyzed previously. After that, a new research design was proposed during 2018 and implemented during the first months of 2019, with the aim of avoiding—or at least attenuating—those difficulties observed in the previous fieldwork. The new results showed interesting differences and few similarities when compared with the other experience. In this chapter, both experiences are analyzed, and lastly, findings and final conclusions are reported.

Keywords: inverse problems, task enrichment, prospective teachers, analysis of solution strategies, sketches, mathematical modeling

1. Introduction

In the last decade, STEM education has become an important topic, deeply analyzed by several authors, particularly in North America and Europe [1–6].

It must be remarked that the conjunction of the subjects to which the STEM education refers is not arbitrary. Sciences provide a context for reflection, organization, and action. They propose problems and questions that invite exploration and discovery and provide criteria to classify and organize the natural environment, thus allowing us to deepen into its richness and complexity. Technology and engineering offers tools and techniques that make the construction of models and artifacts that resolve conflicts or minimize impacts easier. Mathematics provides a mode of expression and representation and a set of notions and skills that allow interpreting and modeling the environment, providing strategies to invent and solve problems and promote logical and critical thinking. As a consequence, STEM education permits the students to understand the world and interact with it in a critical, constructive, and efficient manner.

The natural link that exists between mathematics and science—which is at the core of STEM education—establishes important challenges for mathematics and science teachers. In particular, the mathematics teacher should know precisely the meaning of mathematical contents, identify the needs of students, diagnose learning problems, and prepare proposals for intervention and instruction for their approach and resolution. The abovementioned is important in all cases of mathematics teaching but especially important when working with STEM students, due to the strong bond between mathematics, science, and technology [7–9].

Besides, for future teachers to carry out these teaching strategies, it is necessary to look for significant situations in which the mathematical and scientific contents acquire meaning, for which it is essential to deepen their meanings (performing the semantic analysis, according to the method of analysis of content), as well as cognitive aspects (plausible expectations, learning stages, limitations, and opportunities, which constitute cognitive analysis) and instructive aspects. Therefore, the didactic analysis [10–13] becomes an important tool for the teacher to carry out teaching strategies that promote the development of the STEM competence of the students.

For these reasons, educational research must respond to the training needs of university students who are going to be teachers in the coming years in order to promote favorable attitudes toward sciences and mathematics.

One of the challenges consists in developing prospective teacher's task enrichment skills, [14] and for this purpose, inverse problems [15, 16] are especially relevant since in many branches of science and technology, typical problems are posed in an inverse form. In previous works we analyzed the particular cases when modeling skills are combined with inverse problems, and we called them inverse modeling problems [17, 18].

In this chapter we consider inverse modeling problems, focusing on their posing for task enrichment purposes. We describe our research carried out during the last 4 years, when working with prospective teachers at the University of Granada, Spain (UGR), and some of our most recent findings are reported and discussed in the following sections.

2. Theoretical framework

In our research relatively simple problems are proposed to prospective teachers. In all of them, only fundamental concepts of calculus, linear algebra, and geometry are necessary to be considered. The idea is to analyze easy problems, susceptible of being reformulated in the form of an inverse problem by prospective teachers.

It is expected that the reformulations raised by the participants will be richer than the original and will favor a teaching-learning process based more on exploration than repetition of procedures. As Lester and Cai [19] observed: "…teachers can develop worthwhile mathematical tasks by simply modifying problems from the textbooks" (p. 124).

The latter links the work to be done with a traditional area of research in mathematics education, as is the case of problem posing, the first subsection of our theoretical framework. In the end, the other two subsections are devoted to inverse problems and mathematical modeling.

2.1 Problem posing

There is a long tradition in the literature in English regarding problem-solving research, and the work of Brown and Walter [20, 21] and Kilpatrick [22], among others, represents some of the best known examples. Under the common denomination of "problem posing," these authors include the formulation of new problems and/or the reformulation of problems previously proposed, in a certain format that can be more or less structured [23–26].

A particular case worthy of study occurs when students pose a new problem during the resolution of one of greater complexity [27]. This situation can already be seen in the work of Polya [28] that proposes, as a possible strategy, the approach of the problem in a different way or the establishment of variants, discarding some of its conditions.

In works done by other researchers, the formulation of problems does not have to be linked to the resolution of a specific problem. For example, in some cases the invention of problems is proposed starting from a certain situation or experience [23, 24].

Another option is to combine the two previous approaches and ask students to solve a problem after changing a condition or the final question of the problem, thereby creating a new problem [23].

Other researchers such as Brown and Walter [20, 21] propose a strategy to raise new problems that they call "What if not?" consisting in changing conditions, restrictions, etc. of a certain problem and then generating a new one.

Stoyanova [29] identifies three possible ways in terms of the formulation and invention of problems: free situations and semi-structured and structured situations. In the first of the aforementioned, there are no restrictions on the invention of problems. In the semi-structured, the problem-based approach is proposed, based on any experience or quantitative information. Lastly, in the structured situations, a certain given problem is reformulated or some condition of it is changed.

In our research in Granada, the participants are given a direct problem, which should be reformulated in the form of an inverse problem. Therefore, this can be considered as a structured situation, following the classification given by Stoyanova [29].

2.2 Inverse problems

According to Groetsch's [15, 16] ideas, the process of solving a direct problem can be schematized as in **Figure 1**.

In contrast, inverse problems may have multiple solutions or simply no solutions, thus making them more interesting though consequently more difficult [30]. In essence there are two types of inverse problems; firstly, the causation problem, where the procedure is well-known and the question is concerned with the necessary data in order to obtain a given result. This situation is schematized in **Figure 2**.

The other inverse problem found is the specification problem, where data and result are given and the question is concerned with which procedure can let reach the desired result (output) with the chosen data (input). This process is schematized in **Figure 3**.

Both of these problems are common in the experimental sciences and real-life situations, as noted in previous research [31, 32].

Figure 1.
Scheme for direct problems.

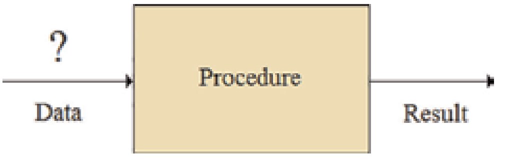

Figure 2.
Scheme for inverse causation problems.

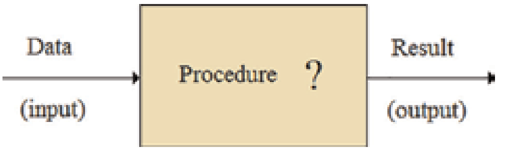

Figure 3.
Scheme for inverse specification problems.

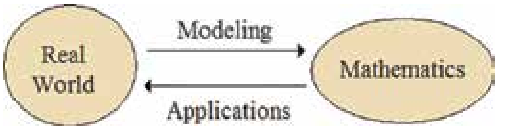

Figure 4.
Comparison scheme between modeling and application problems.

2.3 Mathematical modeling

In the preliminary discussion document to the International Commission on Mathematical Instruction (ICMI) Study 14 [33], the term "modeling" focuses on the direction that goes from the real world toward mathematics, whereas the term "applications" implies the opposite direction. In addition, the term "modeling" emphasizes the process that is taking place, while the word "applications" stresses the object involved, particularly real-life cases that are susceptible to mathematical manipulation. Taking into account these ideas, we arrive at the following schema (**Figure 4**).

An extended discussion about modeling and application problems in our previous research can be found in papers [31, 34].

3. Our previous experiences at UGR master courses

In the University of Granada, the research was designed to work with one or more groups of prospective mathematics teachers for secondary education. Taking into account the available options, we chose to work with the students of groups A and B from the course named "Learning and Teaching Mathematics in Secondary School," included in the Master's Degree in Teaching Secondary Education [14].

In the 2016–2017 academic year at the University of Granada, group A consisted of 33 students, and 41 students formed group B, with regular class attendance. Two of the master courses' university professors collaborated on our research.

In a first class, the prospective teachers of both groups worked on a problem about the filling of a swimming pool. In the first session of the fieldwork, the aforementioned problem was proposed—in the form of a direct problem—and future professors were asked to reformulate it as part of a task enrichment proposal to be used in secondary school courses.

The productions of the prospective teachers of both groups underwent a first analysis, and among all the reformulations presented, three of them were highlighted and selected since they had been posed spontaneously in an inverse form. They were particularly interesting, one of them was proposed by a participant from group A, and the other two were proposed by members of group B.

Then, in a second work session, showing these reformulations, they were given a brief explanation about direct problems and inverse problems. At the end, prospective teachers proposed a new direct problem: the sheep problem.

Unlike what happened with the problem of the pool, in this case the participants were asked to reformulate the problem in an inverse manner for task enrichment purposes.

When those prospective teachers worked with the sheep problem, nine different groups of inverse problems were identified—some of them including up to four variants—and in almost all cases the participants added to their proposal the corresponding task analysis. The productions and the most creative reformulations were analyzed in a previous book chapter [14]. Brief descriptions of the nine groups of inverse problems are the following:

1. Reformulations based on the inverse function, asking the length of the rope given the ratio of area

2. Trivial reformulations

3. Inverse problem asking the location of the peg at which the sheep is tied

4. Inverse problem asking the side of the square

5. Optimization problem, including two sheep and asking for the length of rope in which the accessible area without intersection is maximum

6. Sequential inverse problem, in which, from a given R_0 given and an accessible area A_0, the student has to define a sequence of R_n, in which, the area between R_{n-1} and Rn, that is to say, $A_n - A_{n-1}$ is A_0, and find out the value of n such that it is not possible to find the corresponding R_n

7. Incremental problem, in which, given a length of rope, the student asks the increment in the length in order to increase the accessible area by a certain percentage

8. Dynamic problem, in which the student includes new magnitudes, such as speed

9. Equivalent area problem, given different locations of the peg, in which the student asks the length of rope such that the accessible area remains invariant

After that experience, it was observed that several prospective teachers were particularly creative in both the reformulation itself and in the tasks enrichment; however, the vast majority opted for a standard approach and, in some cases, for a trivialization of the problem.

For these reasons, a new research design was proposed during 2018 and implemented during the first months of 2019, with the aim of avoiding—or at least attenuating—those difficulties observed in the previous fieldwork. As an example, in the year 2017 fieldwork, the participants were not asked to solve their proposed problems, so this was an aspect that needs to be improved in further research.

The new results showed interesting differences and few similarities which are analyzed in the next sections.

4. Fieldwork and results

In this section we start considering the sheep problem in its original version, posed in a direct form. After that we show some of the most creative reformulations proposed by the prospective teachers who participate in the fieldwork at UGR. Finally, we conclude with some general remarks about the productions of the prospective teachers in this experience.

It is important to mention that the following results represent part of the general research about task enrichment by prospective teachers (see, for instance, [14]). In this opportunity our work is focused on the mathematical content of the proposals. Other aspects of the didactic analysis, like the cognitive and the instructional dimensions of the enriched tasks, will be part of further research.

4.1 The sheep problem

In this problem, a sheep is grazing in a square field with side length L. The sheep is tied at the point $(L/2, 0)$, and the rope attached to the sheep has a length R as shown in **Figure 5**.

In **Figure 5**, A represents the area of the sector where the sheep may graze, $r = \frac{R}{L}$ is the ratio of the rope length to field side length, and represents the fraction of the total area accessible for the sheep. It can be observed that f is a function of the ratio r that can be obtained by integration techniques.

Typical exercises consist in supplying students with this figure and asking them to obtain f corresponding to one or more values for r. However, a more interesting approach is to ask the students to draw a diagram hoping they realize that the problem can be solved as an intersection of circles and squares. Four different situations may happen:

- When $r \in [0, 1/2)$, the sheep does not reach the lateral edges of the field.

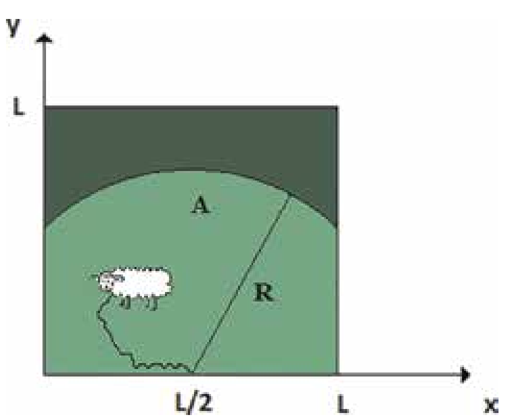

Figure 5.
Part of the field accessible for the sheep.

- When $r \in [1/2, 1)$, the sheep can reach the lateral edges, but not the upper one.
- When $r \in \left[1, \frac{\sqrt{5}}{2}\right)$, the sheep can reach the top edge of the field, but not the whole field.
- When $r \geq \frac{\sqrt{5}}{2}$, the sheep can graze all around the field.

This problem requires modeling and integral calculation, and it can be easily converted into an inverse problem. It is obvious that for every value of $r \geq 0$ there exists a unique value of A, but more challenging is to ask the question from another angle. For instance, for any value of A, does a corresponding unique value of r exist or not? To solve this problem, the function $f(r)$ must be studied in terms of continuity and growth with $r \geq 0$, in order to ensure its invertibility.

4.2 The new fieldwork design

As it was mentioned, the new fieldwork was designed in order to avoid, or at least attenuate, the difficulties observed in the previous experience, carried out during year 2017. In particular, both experimental designs had three main differences:

- Prospective teachers were asked to solve the original direct problem, before proposing their inverse reformulations.
- Before proposing to them this new task, several examples about inverse problems were discussed. However, none of them were about the sheep problem. The main reason for this decision was to avoid simple imitation or adaptation of a given model.
- Prospective teachers were asked to solve their own reformulated problem—or at least write a sketch of the solution—with the aim of reducing the number of non-well-posed problems.

This new design produced different responses that cannot be included in the previous nine groups observed during the year 2017 experience. Some of the most creative and new proposals are analyzed in the following subsection.

4.3 Some of the most creative reformulations for the sheep problem

As already stated, some of the prospective teachers' productions cannot be classified into the nine groups observed in the previous fieldwork. The following examples illustrate this situation.

Example 1: An unusual specification problem.

One of the prospective teachers solved the direct problem by integration, observing that the circumference equation can be written as $\left(\frac{L}{2} - x\right)^2 + y^2 = R^2$ and then the area accessible for the sheep is $A = \int_0^L \sqrt{R^2 - \left(\frac{L}{2} - x\right)^2} dx$. After that, he solves the integral by using the change of variables $x = \frac{L}{2} - R \sin t$ and several well-known trigonometric formulas to obtain the following long formula:

$A = -\frac{R^2}{2}\left[\arcsin\left(\frac{-L}{2R}\right) - \arcsin\left(\frac{L}{2R}\right) + \frac{1}{2}\left(\sin\left[2\arcsin\left(\frac{-L}{2R}\right)\right] - \sin\left[2\arcsin\left(\frac{L}{2R}\right)\right]\right)\right]$ It is easy to observe that this formula can be simplified, but the prospective teacher leaves it in the long version, as shown above.

After this classical solution, his inverse reformulation proposes to get the solution in a geometrical way and compare the final result with the one obtained by integration.

This is a very interesting specification problem, since the data and final result are known and he asks for another procedure in order to get the desired result.

When the prospective teacher solves his own reformulation, he divides the area accessible for the sheep into three parts, a circular sector and two triangles, as it can be observed in **Figure 6**.

In **Figure 6** both triangles have a height h that can be easily obtained by Pythagoras' theorem, giving $h = \sqrt{R^2 - \frac{L^2}{4}}$ and then the area of each triangle is $\frac{1}{2}\frac{L}{2}\sqrt{R^2 - \frac{L^2}{4}}$. After that, the angle α in both triangles is determined by using trigonometric concepts, for instance, $\alpha = arctan\left(\frac{2h}{L}\right) = arctan\left(\frac{2}{L}\sqrt{R^2 - \frac{L^2}{4}}\right)$, and so, the angle of the circular sector, $\pi - 2\alpha$, is easily obtained. Then, the accessible area can be written as

$$A = \frac{L}{2}\sqrt{R^2 - \frac{L^2}{4}} + \pi R^2 \frac{\pi - 2arctan\left(\frac{2}{L}\sqrt{R^2 - \frac{L^2}{4}}\right)}{2\pi}.$$

The prospective teacher shows that both formulas give the same results for particular values like $R = \frac{L}{2}$ and $R = \frac{L}{\sqrt{2}}$. The participant ends his work observing that "as it was expected, both methods gave the same results."

It is important to remark that in the previous experience, carried out in 2017, all the reformulations (i.e., the nine groups and their variants) corresponded to causation inverse problems. None of them proposed an inverse specification problem as in this creative production.

Example 2: An arc length inverse problem.

Another prospective teacher solved the direct problem by using integrals and the same change of variables showed above. Nevertheless, he used other trigonometric formulas, and he takes advantage of symmetry arguments to get a different formula:

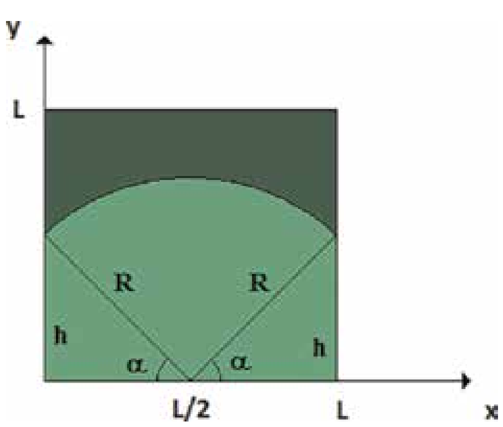

Figure 6.
The accessible area divided into three parts.

$$A = \begin{cases} \frac{1}{2}\pi R^2 & \text{if} \quad 0 \leq R \leq \frac{L}{2} \\ R^2\left(\frac{L}{2R}\sqrt{1-\left(\frac{L}{2R}\right)^2} + \arcsin\left(\frac{L}{2R}\right)\right) & \text{if} \quad \frac{L}{2} \leq R \leq L \end{cases}.$$

So, as it can be observed, he considered two different situations, depending on the comparison between R and $\frac{L}{2}$. It is important to mention that other radii greater than L are not considered.

In the inverse reformulation, he proposes to give this piecewise function as part of the data. He informs that the shepherd decides to eliminate the rope and, instead of it, he wants to build a circular fence like in **Figure 5**, i.e., the same as in the original problem. This fence costs 15 €/m, and the prospective teacher asks for the final cost as a function of variable R.

As it can be easily observed, the problem could be solved in a direct way, by using the arc length formula and then calculating the corresponding integral and lastly multiplying by the cost per meter. However, this solution does not use the given area function—the input of this problem—so it cannot be considered as the solution required, at least for this proposed reformulation.

The prospective teacher solves his own problem by differentiating the given function, since he claims that $L = \frac{dA}{dR}$. This statement—given without any demonstration or justification—is not true for every region in $\mathbf{R}^2$, although it is correct in this case, since it is composed of a circular sector and triangles. A more detailed discussion about when the derivative of the area gives the perimeter can be read at [35]. Finally, after obtaining $L(R)$ by differentiation, the price is easily obtained multiplying by the cost per meter.

In our previous experience, in 2017, only one prospective teacher proposed a reformulation involving arc length in a problem where two sheep were running, one along a straight line and the other along the circumference. In that problem, the accessible area did not appear as an input, so the presence of the arc length can be considered as the unique weak connection between both proposals.

As it was commented, the participant solution is not general, though it is simple, short, elegant, and accurate for this particular situation. As in the previous example, this proposal cannot be included in one of the nine groups observed in 2017.

Example 3: An inversion by intervals.

One of the prospective teachers proposed another interesting inverse reformulation that cannot be classified in the nine groups previously obtained in 2017.

Firstly, he solves the direct problem, changing the axis position such that the new origin is located in the point where the sheep is tied. Due to this change, the accessible area can be obtained as $A = \int_{-L/2}^{L/2}\sqrt{R^2 - x^2}dx = \left[\frac{x}{2}\sqrt{R^2 - x^2} + \frac{R^2}{2}\arcsin\left(\frac{x}{R}\right)\right]_{-L/2}^{L/2}$. After some algebraic manipulations, he arrives at $f(r) = \frac{1}{2}\sqrt{r^2 - \frac{1}{4}} + r^2\arcsin\left(\frac{1}{2r}\right)$. Later, he will use this formula for solving the corresponding inverse problem.

In his reformulation, the prospective teacher proposes that between 60 and 70% of the field is needed for the sheep to graze and between 30 and 40% is needed for a pumpkin plantation, and he asks for at least one value of r that makes both percentages possible.

In the solution of his own inverse problem, he makes mistakes in the derivative of $f(r)$; nevertheless, his conclusion about the growth of this function is obviously right. For this reason he tries with particular values, like $f(1) \cong 0.956$ and

$f(0.5) \cong 0.3926$, and after some iterations, he concludes that $f(0.7) \cong 0.625$, so $r = 0.7$ is a possible answer.

The proposal itself seems to be not as creative as the previous ones (Examples 1 and 2), but it is the only one that asked for the pre-image of an interval, an interesting topic related to continuity, monotony, and derivatives, among other important calculus concepts.

Example 4: General inversion of a vector function.

Another prospective teacher tries to solve the direct problem by integration. For this purpose he puts the area accessible for the sheep as $A = \int_0^L \sqrt{R^2 - \left(\frac{L}{2} - x\right)^2} dx$, and he proposes the change of variables $x = \frac{L}{2} - R \sin t$. Unfortunately some mistakes when using trigonometric formulas led him to a wrong result $f(r) = \frac{5}{4} r^2 \arcsin\left(\frac{L^2}{2} r\right)$. He does not use this function in the inverse problem proposal, but it appears again in the corresponding solution.

The reformulation considers the same situation schematized in **Figure 5**, like in the original problem, and he asks to obtain L and R for given values of f and r. In other words, the input is the vector (L, R), and the expected output is another vector (f, r); then, it corresponds to a vector function inversion.

The solution is wrong and easier than it should be, since he considers the function previously obtained $f(r) = \frac{5}{4} r^2 \arcsin\left(\frac{L^2}{2} r\right)$, which is simpler than the correct one: $f(r) = \frac{1}{2}\sqrt{r^2 - \frac{1}{4}} + r^2 \arcsin\left(\frac{1}{2r}\right)$. If the wrong $f(r)$ is utilized, it follows that $\frac{4f}{5r^2} = \arcsin\left(\frac{L^2}{2} r\right)$, and then L can be obtained as $L = \sqrt{\frac{2}{r} \sin\left(\frac{4f}{5r^2}\right)}$. Finally, this L can be multiplied by r to obtain R.

It is obvious that the inverse problem was unwittingly simplified; however, it is an interesting proposal and the only one of this type in both years 2017 and 2019. Another important characteristic is that it requires a general inversion, since the input vector (L, R) is a generic vector of the vector space $\mathbf{R}^2$.

Example 5: Problems that ask for a sketch of the region.

Four prospective teachers (two in each group) proposed inverse problems that ask for a sketch of the region, with different variants.

In the first one, the axis are chosen such that the sheep is tied at the origin of the coordinate system, and so, the accessible area can be obtained as $A = \int_{-L/2}^{L/2} \sqrt{R^2 - x^2} dx$. In her reformulation, the prospective teacher gives the integral, and the problem consists in doing a sketch of the region, including an identification of its elements.

The second one is similar, but there are no axis changes, and the accessible area is given by the formula $A = \int_{-\arcsin(L/2R)}^{\arcsin(L/2R)} R^2 \cos\theta \sqrt{1 - \sin^2\theta} d\theta$. The prospective teacher informs that this formula was obtained after performing a change of variable $x = R \sin\theta + \frac{L}{2}$, and, like in the previous case, she asks for the region involved.

The last two cases are different since in both of them the student is asked to propose a criteria that allow to choose between regions **(a)** and **(b)**, for any given value of the accessible area A (see **Figure 7**). The solution can be obtained by considering the limit case, i.e., $R = \frac{L}{2}$ and then $A = \frac{1}{2}\pi R^2 = \frac{1}{2}\pi\left(\frac{L}{2}\right)^2 = \frac{1}{8}\pi L^2$. So the requested criteria is very simple: if $A > \frac{1}{8}\pi L^2$, the region is like **(b)**, whereas if $A < \frac{1}{8}\pi L^2$, the region is like **(a)**.

It can be noted that in those cases, the problem has a weak connection with the sheep problem, since the context about the sheep, the rope, etc. can be eliminated from the proposals, and the solution remains unchanged.

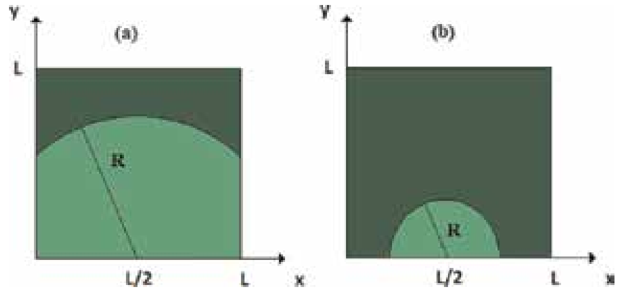

Figure 7.
Two possible cases for the accessible area.

Example 6: Interpretation problems.

A couple of prospective teachers proposed a different kind of inverse problem, where the elements of **Figure 5** are explained. After that, one of them gives the following function as a data for the inverse problem: $f(r) = \frac{1}{2}\left[\sqrt{r^2 - \frac{1}{4}} + 2r^2\arcsin\left(\frac{1}{2r}\right)\right]$. She only mentions that f and r express relations between the variables and the problem consists in determining the meaning of both.

In the last one, the situation proposed is almost the same, but there is a mistake in the given function f; so, the correct answer will be that r has no meaning.

As it happened in the other examples commented above, this kind of inverse problem did not appear in the year 2017.

5. Discussion

Problem posing has an important role to play in the STEM classroom. For instance, Beal and Cohen [36] suggested "… significant changes to the existing model of education, in which students would move from passive consumers of educational resources that have been developed by others to creators of rich, innovative and authentic STEM content…".

Moreover, problem posing has a positive influence on students' ability to solve word problems and provided a chance to gain insight into students' understanding of mathematical concepts and processes.

Some researchers have found evidences that students' experience with problem posing enhances their perception of the subject; causes excitement and motivation; improves students' thinking, problem solving skills, attitudes, and confidence in mathematics; and contributes to a broader understanding of mathematical concepts [37].

Some of these capabilities were observed in our fieldwork with prospective teachers, particularly in the selected examples, where some responses were very creative. This is an important aspect not only for teaching but also as a prominent feature of mathematical activity. As Poincaré said "Mathematicians may solve some problems that have been posed for them by others or may work on problems that have been identified as important problems in the literature, but it is more common for them to formulate their own problems, based on their personal experience and interests" [38]. In the same way, Hadamard [39] identified the ability to find key research questions as an indicator of exceptional mathematical talent. For instance, a challenging question appears in the solution of Example 2 of the previous section, where the arc length is obtained as the derivative of the area accessible to the sheep. The question about the accuracy of this procedure led us to an interesting research question whose answer is not trivial (see [35] for a general discussion).

In our study there were challenging proposals which not always were possible to be solved by the prospective teachers. This fact is in accordance with Silver and collaborators, who remarked that "… mathematicians certainly pose mathematical problems or conjectures that they are not certain they can solve (e.g., Goldbach's Conjecture), and research with adult subjects has found that they often pose mathematical problems that they could not solve on their own" [27]. This situation takes place in Example 4, where the inverse reformulation was solved only because the problem was unwittingly simplified.

Taking into account that the participants are prospective teachers, it is important for them to be able to create new problems to work on their classes. Moreover, as Silver noted "Problem posing has figured prominently in some inquiry-oriented instruction that has freed students and teachers from the textbook as the main source of wisdom and problems in a school mathematics course" [23]. For this purpose, Kilpatrick [22] argued that one of the basic cognitive processes involved in problem posing is association: "[Because] knowledge is represented as a network of associated ideas, that network can be used to generate problems by taking a concept node in the network and raising questions about its associates" (p. 136). In our research, unexpected association of ideas was found in several proposals, like in Example 1 where different ideas from calculus and trigonometry were combined in a very creative proposition.

Finally, motivation is a very important issue which was also relevant in this experience. It deserves to be mentioned that some of the prospective teachers pose up to three different reformulations of the given direct problem, which can be considered as a result of a motivating activity. This fact was also observed by Winograd who reported that students in his study appeared to be highly motivated to pose problems that their classmates would find interesting or difficult [40].

6. Conclusions

The first immediate conclusion is that the results of both experiences—carried out in 2017 and 2019—are absolutely different.

In 2017 the prospective teachers imitated previous examples provided for the first problem, i.e., the filling of a swimming pool. When they were asked to reformulate the second one (the sheep problem), there were no examples that can be imitated, but they followed the same ideas that they used in their proposal for the swimming pool, like inverting the function, changing the geometry, or including obstacles, among others.

On one hand, in 2019 the previous examples were very simple and concerned other mathematics topics like proportions, arithmetic and geometric sequences, and solving for unknown sides and angles in right triangles. On the other hand, the prospective teachers were asked to solve the direct problem before proposing their own reformulation. So, in this new fieldwork, their experience was more involved in the mathematical solution of the direct problem than other inverse reformulations. It can be observed that this fact led the proposals in many different ways. For instance, they gave a formula in the reformulated problem and asked for an interpretation, a sketch of the corresponding region, or another way to get the same result without using integrals.

Other important difference is the use (or not) of external variables, which can be physical (time and velocity), chemical (amount of fertilizer and herbicide), economical (cost of a fence), or biological variables (like kilograms of grass per day). Those variables were widely used in 2017; however, in 2019 they only appear in a few cases, like in the Example 2, in Section 4.

Another remarkable observation is that the proposals corresponding to 2019 are usually more challenging from a pure mathematical viewpoint. For instance, they ask for different types of solutions (analytical, geometrical, etc.), and they need the analysis of monotony, existence of a pre-image, solving nonlinear equations, etc. They also ask for more conceptual issues, like identify a region or give a meaning to one or more given variables in a certain formula, among other options that were absolutely unusual in 2017.

It can also be observed that the proposals in year 2017 were more practical, i.e., hands-on problems more involved with other disciplines and more connected with the reality and its mathematical modeling, whereas in 2019 they are more conceptual, mathematically challenging, and self-contained.

As a general conclusion, it seems that the prospective teachers tend to propose the reformulations based on their own recent experiences. If these experiences consist in working with previous examples, they try to imitate them, and if their experience consists mainly in solving the direct problem, they tend to use this solution—or the process that led to it—as the main input for problem posing.

Finally, it is difficult to say that one of these experiences yielded better results than the other. In fact, in one of these experiences, certain characteristics predominated, while in the other one, different characteristics were observed. As a consequence, the resulting proposals more than antagonistic can be regarded as truly complementary.

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Chapter 4

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

Bing Wei and Yue Chen

Abstract

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

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

1. Introduction

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

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2. Redefining the integrated STEM education in K-12

2.1 Why STEM education?

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

2.2 Various standpoints of integration

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

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

2.3 Elements of integrated STEM education

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

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

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

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

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

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

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

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

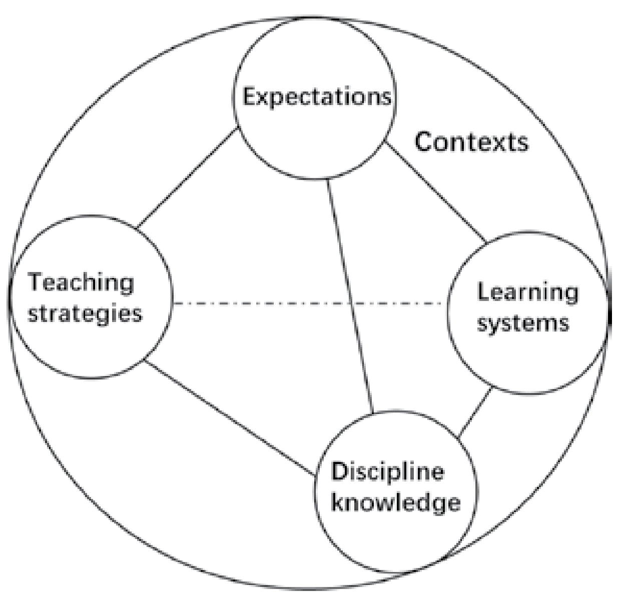

Figure 1.
An ideal model of integrated STEM education.

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

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

3. Integrated STEM education in action

3.1 How to integrate STEM education in K-12

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

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

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

3.2 Enactment of integrated STEM education

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

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

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

4. Conclusions and implications

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

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

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

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Chapter 5

'Making' as a Catalyst for Engaging Young Female Adolescents in STEM Learning

Karen Hyllegard, Jennifer Ogle and Sonali Diddi

Abstract

STEM enrichment programs have demonstrated positive impacts on young female adolescents' interest and aptitude in STEM, personal/social-psychological well-being, and educational aspirations. Introducing STEM knowledge and skills in an environment of 'making,' that is, in a setting of hands-on activities, may further enhance adolescent girls' engagement in STEM learning. The maker movement, defined as the convergence of technology and traditional artistry, has generated interest among educators for its potential to nurture STEM learning, including its capacity to engage diverse populations of youths in the making of creative objects through experimentation in science, technology, engineering, and math (i.e., STEM-based making). STEM-based making is a way to support young girls, who often approach making from an esthetic or personal expression perspective, to more fully integrate systems and technologies that advance critical thinking, innovative prototyping, and problem-solving into the making process. Insights are presented as to how STEM-based making designed for young female adolescents—a group that has traditionally had limited access to extracurricular STEM experiences as well as to makerspaces—may foster greater access to, and equity in, STEM learning. The role of universities in facilitating access to and equity in STEM-based making also is addressed.

Keywords: education, STEM, making, adolescent girls, universities

1. Introduction

In the United States, women are significantly underrepresented in the science, technology, engineering and mathematics (STEM) fields, although to a lesser degree than has been the case in the past [1]. A recent survey indicated that although women made up almost half (47%) of the U.S. workforce, only 25% of women held STEM-related jobs [2]. Further, although almost an equal number of women and men hold science and engineering degrees in the US, only a small percentage of women are employed as scientists and engineers [3]. Women and minorities are especially underrepresented in the physical sciences, computer sciences, and engineering [4, 5]. And, although STEM professions grew by 24.4% from 2005 to 2015, women and minorities were not well-represented in this job growth [6].

By 2020, it is projected that U.S. companies will need 1.6 million STEM-skilled employees, with labor market data indicating that core STEM knowledge, skills, and abilities are crucial not only in conventional STEM occupations, but also in a host of other job sectors [5, 7]. The need to develop a balanced and inclusive human resource pool prepared to tackle STEM challenges is further supported by data indicating that, currently, in the US, there are more vacancies in the STEM fields than there are people in the STEM workforce [8, 9]. Thus, it is imperative that initiatives and programs from the government and commercial sectors be designed to specifically recruit and retain women and other underrepresented minorities in order to reduce the gap in the STEM workforce [5]. Establishing a strong and diverse STEM workforce will foster creativity, innovation, and problem-solving skills to ensure America's continued economic growth [10, 11].

In order to successfully address women's underrepresentation in the STEM workforce, it is important to broaden the participation of girls in diverse and exciting STEM education programs, both formal and informal, both in-school and out-of-school, that demonstrate the relevance of STEM learning to everyday life, to educational and professional opportunities, and to solving "real world" problems. Programs designed to heighten interest in STEM learning among adolescent and teenage girls are especially important owing a variety of identified barriers to girls' persistence in STEM education. According to American Association of University Women (AAUW), girls' interest and performance in STEM subjects is greatly affected by stereotypes, gender bias, and loss of confidence regarding their academic achievement in STEM-related courses [12]. Misconceptions regarding STEM and its relevance lead young girls to feel that STEM careers are 'not for them.' Loss of interest and negative attitudes toward STEM careers among girls take root early, during their middle school years, and progress rapidly [13]. Further, middle school girls often perceive STEM-related subjects as uninteresting and difficult [14].

In recent years, educators have made efforts to encourage girls to persist in STEM learning. Evidence suggests that this educational support to girls must start early—in elementary and middle school—rather than in high school [12, 15]. Efforts have been made to identify the forms of educational support that will best nurture girls' STEM interest and learning as well as their confidence to pursue a STEM career. First and foremost, educators must capture girls' attention with an engaging and relevant curriculum and incorporate activities into that curriculum that inspire girls to pursue STEM careers [16]. According to a 2018 study, integrating "real world" problems into STEM curricula can especially be meaningful for girls insomuch as tackling such problems helps to align girls' interests, values, and desires to make an impact through pursuit of a STEM career [17]. Similarly, incorporating hands-on, 'learning and doing' activities may help girls to build critical thinking skills and abilities related to gathering, evaluating, and analyzing evidence to solve today's multifaceted problems [18]. Additionally, exposing girls to positive female role models—especially those who share a background with the young female participants—helps to undermine girls' negative stereotypes about STEM as well as the belief that STEM careers are "not for them" [16]. Immersing girls in STEM learning also may help girls to envision STEM as a realistic part of their academic and professional futures [16].

One approach to immersing girls in STEM learning involves the integration of art, creativity, and design into the learning experience (aka STEAM); or, more specially, learning that embraces the enjoyment and achievement realized from the creation of physical objects—prototypes and/or esthetic and functional items—and that simultaneously demonstrates principles of science, technology, engineering and math [19–21]. This 'product-oriented' approach to learning purposefully embeds creativity into the learning process and positions students as active creators, rather than as passive consumers (Loudon, 2018). Product-oriented learning that marries creativity with advanced technology is the foundation for the modern 'maker' or 'making' movement that is receiving considerable attention across U.S. communities and educational institutions for its potential to foster STEM learning and career opportunities, especially among underrepresented groups such as girls. Although girls may not often associate creativity with STEM occupations or with the ability to make a difference in the world through STEM [17], creativity is integral to many STEM professions. Creativity involves use of the imagination to generate original and valuable ideas or objects, and thereby contributes to complex problem solving in science, technology, engineering and math [22]. An empirical study exploring the relationship between problem-solving, creativity, and interest in STEM revealed that girls' interest in problem-solving was a predictor of their interest in all four STEM subject areas and that girls' interest in creativity was a positive predictor their interest in computers and engineering [11]. Further illustrating the importance of creativity in STEM professions, the World Economic Forum's [23] job report identified analytical thinking, innovation, active learning, and proficiency in new technologies (design and programming) as well as 'human' skills, such as creativity, originality and initiative, critical thinking, persuasion and negotiation and complex problem-solving as important workplace skills that will retain or increase their value by 2022.

With this chapter, we address the potential of making to serve as a catalyst for engaging young female adolescents in STEM learning. More specifically, we explore how STEM-based making may encourage young female adolescents, who often approach making from an esthetic or personal expression perspective [24], to more fully embrace and integrate systems and technologies that foster creative and critical thinking, innovative prototyping, and problem-solving into the learning process. Additionally, we present insights as to how STEM-based making designed specifically for young female adolescents—a group that has traditionally had limited access to extracurricular STEM experiences as well as to makerspaces owing to age, gender, and socioeconomic status [25, 26]—may foster greater access to, and equity in, STEM learning. We conclude by exploring the role of colleges or universities in facilitating access to and equity in STEM-based making through an in-depth look at three STEM education programs that were established by faculty at U.S. universities specifically to provide adolescent girls the opportunity to engage in experiential STEM learning in resource-rich environments.

2. Engaging young female adolescents in STEM learning

2.1 Making and makerspaces

The maker movement, defined as the convergence of technology and traditional artistry, is generally associated with informal learning that encourages exploration, discovery, and understanding [27]. Making may take many forms and encompasses a variety of activities, such as design thinking, building, testing, and modifying, that are oriented toward the creation of a physical object. Making fosters collaboration and experimentation, and it involves a trial and error approach to problem-solving, wherein failure is recognized as positive part of the learning experience [28]. Making introduces learners to a variety of disciplines and encourages them to assume multiple roles, such as designer, computer scientist, material expert, mathematician, and inventor, and to utilize diverse experiences, knowledge, methods, and skills to identify innovative solutions to simple and challenging problems [28]. It also presents opportunity for more diverse teaching roles, in the form of mentoring and peer teaching, than are typically available in a traditional school setting [29, 30].

The maker movement is grounded in constructionism and constructivism theories, which posit that creation-based experiences are foundational to learning [31, 32]. In particular, constructionist and constructivism principles propose that learning is best supported when students engage with tools and technologies to make physical objects through authentic, hands-on experiences that incorporate guided, peer-supported, collaborative processes [31, 32]. Hands-on, collaborative experiences—that is, the bringing of people together for the exchange of ideas—help students integrate existing and new knowledge and foster their problem-solving skills. These perspectives also recognize the social aspects of learning, and in particular, the potential for students to learn through "tinkering," an iterative, creative, and playful form of exploration and experimentation with technologies, tools, and materials [33]. In prior work, both peer-supported and tinkering experiences have been linked to positive learning outcomes [34]. Similarly, the hands-on, collaborative, playful, technology-driven qualities of the constructionist "learning by doing" approach provide an apt platform for the introduction and mastery of STEM educational competencies [35]. Further, as world view theory proposes, situating STEM education in the context of students' existing interests, everyday life, or ideas that students find to be significant can be a meaningful way to support STEM learning across diverse disciplines [36].

Today's maker movement is supported by new digital fabrication technologies (i.e., computer aided design + computer aided manufacturing, CAD/CAM) that play a valuable role in prototyping and product development and, in turn, drive innovation [37, 38]. Digital fabrication technologies, or 'digital tools' are one of three components necessary to realize to full potential of making in education; the other two being 'community infrastructure' and a 'maker mindset' [28]. Digital tools include physical tools that shape materials into objects, such as 3D printers, digital embroidery machines, and laser cutters as well as logic tools or programmable devices (i.e., microcontrollers) that process input from sensors, switches, and internet data to control output devices, such as LEDS. The growing affordability of these tools offers the potential for increased accessibility to making across the population [28]. The second component of the maker movement, community infrastructure, which includes both online and offline access to information, inspiration, and mentoring, is especially critical to engaging youth in making. Learning or making communities have the capacity to foster interest, identity, and learning among youth; when youth are interested in a subject or activity and when that subject or activity aligns with their identity and when they feel connected to a community founded upon shared interest in that subject or activity, there is tremendous opportunity for learning [39]. The third component, maker mindset, refers to the values, beliefs, and dispositions that characterize individual engagement in a maker community.

Drawing from prior work, Martin [28] presented four elements of the maker mindset required to harness the full value of making in education. The first element is experimental play, which implies that making is viewed as a fun, enjoyable activity or pleasant experience in an environment that encourages experimentation and learning. The second element is the asset-oriented or growth-oriented nature of making, which embodies a free-choice approach to 'what' to make and encourages the belief that anyone can learn to make. The third element, failure-positive, fosters understanding of the role that failure plays in making and learning. This is the recognition that failure is important to the creative process because it necessitates more critical thinking or tinkering to achieve envisioned solutions to simple and challenging problems. The fourth element is collaboration, which involves a willingness to share ideas and information with others, to assist and support others in their making endeavors, and to connect with others through the activity of making [40].

Makerspaces are defined as places where 'likeminded' individuals come together to exchange ideas, learn skills, share knowledge, and utilize technology and tools to create objects [41] and represent the collective manifestation of digital fabrication technologies, community infrastructure, and a maker mindset. Makerspaces emphasize hands-on discovery in an increasingly automated world, and although they vary considerably with respect to the scope and sophistication of the technology and tools available, well-equipped spaces often include computers as well as design and engineering software; 3-D printers; audio and video capturing/editing tools; wood, metal, and glass making equipment; digital textile printers, embroidery, and knitting machines; sewing machines and/or fabric welders; and/or commercial cooking equipment. Makerspaces typically require partnerships among varied stakeholders, including makers—artists and scientists, community members and organizations, government representatives, educators, digital technology and equipment companies, and others—to inform best practices for the creation of well-equipped makerspaces that ensure equity-oriented use, exploration, and learning as well as to meet the financial cost of creating such spaces. Additionally, makerspaces that embody the four elements of the maker mindset—experimental play, free choice, positive failure, and collaboration—are most likely to realize the full value of making in education [28]. Makerspaces may support a maker mindset by providing an array of technologies, maximizing open, unstructured use time, offering a variety of free or inexpensive materials, and employing experts or mentors with diverse backgrounds and varied making skills.

2.2 Equity in STEM learning through access to making and makerspaces

Making has generated interest among K-12 educators for its potential to foster STEM learning, including its capacity to engage youth, in the hands-on creation of esthetically-pleasing objects informed through experimentation in science, technology, engineering, and math (i.e., STEM-based making). In particular, making has the potential to engage youth who may not self-identify as 'good at science,' in STEM learning through the creation of innovative and personally meaning objects (i.e., product-oriented learning) [41]. Further, when STEM knowledge and skills are introduced in an environment of 'making' in a setting of hands-on, art, craft, or design activities, there is evidence that female adolescents, who often approach making from an esthetic or personal expression perspective, may become more engaged in STEM learning [24, 42].

The benefits of STEM learning provided within extracurricular and informal, open learning environments, ranging from after school clubs to summer programs, is well documented (see [43]). Findings from the Harvard Family Research project [44] revealed that extracurricular STEM programs have the capacity to improve attitudes toward school, interest and aptitude in STEM, personal/social-psychological well-being, and educational aspirations, particularly among adolescents from lower-income families. Informal, out-of-school environments typically allow for more independence, creativity, and personal inquiry, all of which have been shown to support STEM learning [43]. Further, participation in STEM clubs and activities outside of school helps boost girls' confidence to pursue a STEM-related career [28]. Kafai et al. [20] exposed seventh and eighth grade Native American students to STEM learning in a summer camp environment, where students engaged in the ethnographic study of electronic textiles to foster learning and participation in computer programming and engineering. After making their own customized, culturally-inspired, electronic textiles using the LilyPad Arduino, the students perceived computer programming to be more relevant to their identities, their daily lives, and their career choices. The students also reported greater engagement in the learning process and greater confidence in their computer programming skills [20]. Similarly, Thuneberg et al. [21] engaged 12–13 year old students in a product-oriented learning workshop for an math and art exhibition that combined creativity, mathematics, and engineering in the making of structures and creatures that embodied the fusion of art and technology and depicted curiosity, imagination, and play. Findings revealed that that the lowest achievers liked learning math through hands-on activities related to the exhibition, and preferred it over learning math in school. For girls, the situational motivation (i.e., the esthetic aspect of the exhibition) was strongly related to attitudes toward technology and sciences, the importance of math, and future educational plans. Another example of an out-of-school, hands-on learning module, combing experimentation and creative modeling to visual DNA-structure, examined cognitive achievement among 9th grade students [45]. The researchers observed positive correlations between cognitive achievement and model quality and cognitive achievement and creativity among female participants, concluding that creative hands-on modeling appears to support girls' science learning.

The maker movement is often acknowledged for its capacity to offer democratic access to advanced technology that previously was only accessible to experts or to privileged individuals; primarily affluent, well-educated, white males [26, 46, 47]. However, the full capacity of making to foster inclusivity, that is, to engage women, youth, ethnic minorities, LGBTQ+ individuals, persons with disabilities, and other underserved communities/populations in STEM learning, has not yet been realized owing to the limited number of makerspaces and making programs that prioritize access for underrepresented groups [46]. A clear divide remains between those with access to well-equipped makerspaces that offer advanced technology (e.g., computers, software, virtual reality), modern machinery (e.g., digital printers, 3-D printers, laser cutters), and expert technicians, mentors, and peer teachers and those without access to makerspaces, which remains a challenging obstacle to equity in STEM learning [42]. Makerspaces do not adequately address barriers to entry (e.g., cost, location) or the exclusionary practices (e.g., membership, enrollment) that limit engagement in making and STEM learning among members of the broader population [46].

Dawson [26] notes that it is critical to establish safe and welcoming learning/making spaces—where all experiences and knowledge are respected and valued—for youth, women, and/or people of minority ethnic backgrounds. Access to maker spaces is often constrained by structural inequalities, yet, such spaces have the capacity to disrupt notions about *who* can engage in STEM learning/making and to provide opportunities for social justice and thereby increase diversity in learning [20, 26]. Ryoo and Calabrese Barton [41] contend that although it is important to continue to address access and opportunity, it is especially important to examine the power structures that shape access. This includes the types of making that are valued, as well as how making and makerspaces address the needs and rights of youth from nondominant communities in ways that are equitable for all youth, especially for youth of color and girls who are historically underrepresented in STEM. Thus, making experiences and maker spaces that specifically account for the needs, rights, and interests of young female adolescents, a group that has traditionally experience limited access to extracurricular STEM programs as well as to makerspaces owing to age, gender, and socioeconomic status [25, 26, 46], may help to foster greater equity in STEM learning.

2.3 University STEM programs for girls: facilitating access and equity in STEM learning

Universities and colleges may be especially well positioned to facilitate adolescent girls' access to equity in STEM-based making and learning. Central to today's university/college campus are well-educated, same gender, faculty and student role models, facilities (e.g., computer and science laboratories) that support higher-order STEM learning, and, more recently, the development of well-equipped makerspaces designed purposefully to engage students in creative and innovative exploration. Equally important is the commitment among today's universities and college to better serve all members of society by demonstrating principles of inclusion, diversity, and social justice, which includes the development and delivery of educational programs for middle school and high school students that are specifically targeted toward underrepresented groups, including members of the Native American and the Latinx communities. Masters et al. [48] have argued, however, that in order for making to be truly inclusive, diverse, and liberatory, the design and operation of makerspaces must extend beyond the domain of education and universities to also involve community leaders and support community goals. Calabrese Barton et al. [25] also considered the role of youth in the purposeful co-design of making opportunities to engage underrepresented youth in STEM. Partnerships between educators, community members, and youth may, in fact, offer the greatest promise for democratic access to makerspaces through the intentional removal of barriers, and may, in turn, offer the greatest potential to achieve equity in STEM learning.

The widespread acknowledgment of the benefits that can accrue from offering girls early, positive, STEM socialization experiences has prompted the development of numerous informal, out-of-school STEM education programs specifically targeting the needs of girls (see [49], for a review). Many of these programs have been developed and facilitated by university faculty and students. Frequently, such programs are offered on university campuses, providing participants access to rich learning resources and immersing them within the stimulating context of higher education. Programming has been offered in diverse formats, ranging from after-school clubs (e.g., Building Girls Up in Science), BUGS [50] to one-day workshops (e.g., Talented At-Risk Girls: Encouragement and Training for Sophomores), TARGETS [51] to nonresidential and residential summer camps (e.g., Fashion FUNdamentals [19]), Camp Reach [52]. Some programs, such as Females Excelling More in Math, Engineering, and Science (FEMMES) have included a mix of program formats to achieve their mission [53–55]. Programs also have targeted girls of varied ages, ranging from elementary school students to undergraduate students, with one unique program—Georgia Computes! [56]—addressing the needs of female students (and underrepresented students of color) throughout the entire educational pipeline, from elementary school through the university experience.

In this section, we highlight three innovative university STEM programs—FEMMES, Fashion FUNdamentals, and Digital Youth Divas—developed to specifically facilitate access and equity in STEM learning among young girls. These programs focus upon the needs of girls in the upper elementary (FEMMES) and middle school years (Fashion FUNdamentals, Digital Youth Divas). As is true of many programs developed for elementary and middle school students, each of these programs aims to provide girls positive experiences with STEM, to maintain and promote girls' interest in STEM, to enhance girls' confidence in STEM, and, ultimately, to increase women's representation within STEM fields in higher education and within STEM careers upon graduation (cf, [49]). We chose to feature the selected programs because participants have evidenced positive outcomes and because these programs integrate characteristics that have been identified as integral to a successful STEM education program for girls, including (a) the creation of an engaging and relevant curriculum that incorporates hands-on/'learning and doing' activities, (b) the integration of 'real-world' activities that inspire career exploration, (c) exposure to positive female role models, and (d) opportunities for immersion in STEM environments [16–18]. Importantly, in differing ways, these programs also incorporate selected components identified by Martin [28] as essential in promoting the full potential of making in education.

2.3.1 Females excelling in math, engineering, and science (FEMMES)

Founded in 2006 at Duke University, FEMMES is a student-managed outreach organization that actively engages girls in STEM fields through experiential activities and mentoring from female university faculty and students. Most FEMMES program components target underserved girls in 4th through 6th grades. Since its inception, FEMMES has expanded to include chapters at multiple universities (e.g., University of Michigan, UNC Chapel Hill, and the University of Chicago) as well as diverse program components, including a one-day 'capstone' experience, a 6-week after-school program, a Saturday program that parallels the content of the after-school program, a summer camp, a hackathon (designed for female-identifying students enrolled in grades 9–12) [54], and a mentorship program (FEMMESConnect) that allows FEMMES participants to build upon their prior involvement in the FEMMES programming. Here, we focus upon selected components of the FEMMES program that have been offered in collaboration with Duke University and that have been formally evaluated within the research literature: (a) the capstone experience [55] and (b) the after-school program [53].

The capstone component of FEMMES is a free, annual, one-day STEM education mentoring program attended by more than 200 4th–6th grade girls enrolled in Durham, North Carolina elementary schools. The event is held in the science and engineering facilities on the Duke University campus and opens with a keynote address. Interactive sessions follow the keynote address and involve participants in small-group, hands-on activities facilitated by university faculty and female student counselors/mentors. The activities reflect the expertise of the female faculty who guide them and focus on conventional STEM topics such as biology, biomedical and electrical engineering, chemistry, computer science, environmental science, math, and statistics. Activities are designed to be engaging and "fun." For instance, in a pharmacology activity, participants consider "pharmacology as sleuths," and in a computer science activity, participants create a 3D interactive story [54, 55].

An assessment of the effect of participation in the 2008 and 2009 capstone events revealed increases in 4th–6th grade girls' interest, knowledge, and confidence in math, science, and engineering from the beginning to the end of the FEMMES program. With the exception of a slight loss of interest in science and engineering, these gains persisted over the next 3 months, suggesting that the combination of hands-on activities and mentorship from female faculty and students may be valuable in inspiring young girls' STEM achievement [55].

The FEMMES after-school program is a free, 6 week STEM education opportunity for 4th–6th grade girls attending selected, underserved elementary schools in Durham, North Carolina. The program curriculum addresses a range of science topics (e.g., biology, chemistry, physics, earth science, and engineering) through hands-on, problem-based approaches that encourage the development of critical, analytical, and teamwork skills. Example activities include a chemistry lesson in which students make ice-cream to understand how salt decreases the freezing point of water and a bridge-building activity in which students explore basic concepts in physics and structural engineering. Programming takes place once per week (1 h per session) at the elementary schools, where girls work in small groups that are facilitated by female undergraduate and graduate student mentors who have been trained to provide encouragement and support to participants and to present material in a manner that engenders enthusiasm in learners. In 2009, the after-school program served 100 students, with a student-mentor ratio of 4:1 [53, 54].

A (combined) evaluation of the 2009 and 2010 FEMMES after-school program offerings revealed that, at the conclusion of the program, girls demonstrated increases in science, interest in engineering, knowledge in science, confidence in math, and confidence in science. Although analyses did not specifically explore aspects of the program most valued by participants, it is possible that the overall positive impact of participation could be linked to various aspects of the program, including the interactions with positive female role models/mentors, the integration of open-ended activities, and/or the incorporation of cooperative learning strategies [54, 55].

2.3.2 Fashion FUNdamentals

Founded in 2015 at Colorado State University, Fashion FUNdamentals is a STEM enrichment program that leverages middle school girls' 'passion for fashion' to build their STEM interest and skills and to foster their self-esteem. The program is grounded in world view theory and research on the maker movement, both of which support the value of connecting STEM learning to girls' existing interests and experiences, including experiential, open-ended, art, design, and craft activities [28, 39, 42, 57]. Fashion FUNdamentals is offered as a two-week summer program (M-F, 9 am–5 pm) that targets underserved girls entering 6th, 7th, and 8th grades; the program is offered free of charge to girls who participate in their schools' free and reduced lunch programs. The program is delivered primarily by female faculty and students on the Colorado State University campus and makes use of the university's state-the-art equipment (e.g., body and foot scanners, digital textile and 3-D printers) and laboratories [19, 58, 59]. To date, a total of 146 girls have been served by the program. In years with larger enrollments, girls are divided into groups of 15–24 and rotate through the program with their cohort.

The Fashion FUNdamentals curriculum includes both technical and social programming components, thereby addressing diverse educational needs of participants. Technical programming is designed to enhance girls' STEM interest and aptitude through engagement in hands-on activities that require application of STEM knowledge to develop solutions to 'real world' problems within the global fashion industry. The development of technical programming curriculum is guided by Colorado Academic Standards in math and science. Technical programming units address fiber/textile science, digital textile design, apparel construction/engineering, apparel costing and pricing, merchandising assortment planning, historic textiles, and wearable technology. Example technical programming activities include (a) using optical microscopes to examine various fibers, exploring synthetic fiber formation through spinning techniques, and dyeing and comparing the qualities of dyes on different fabrics (fiber science unit), (b) employing computer-aided design and digital textile printing technologies to create and print original textile designs (digital textile printing unit), and (c) employing 3-D body scanning technology to measure human body dimensions to calculate critical measurements for garment construction (apparel engineering unit). Because the program aims to foster creativity, girls are provided as much flexibility as possible in shaping what they make (e.g., in developing their textile prints and garment designs). Social programming focuses upon issues of social and psychological concern among middle school girls and is designed to support participants' self-esteem, and thus, their academic performance [60]. Social programming units address anti-bullying, body image/media literacy, internet safety, nutrition, and physical activity (e.g., creative movement, swimming, rock climbing). Example social programming activities include (a) analyzing the meanings and social consequences of messages included in teen fashion magazines and creating t-shirts featuring body positive messages (body image/media literacy unit) and (b) planning, preparing, enjoying, and analyzing the nutritional content of a healthy snack (nutrition unit) [19, 58, 59].

Outcomes of participating in Fashion FUNdamentals have been assessed through the collection of both quantitative and qualitative data. Analyses of quantitative data collected from girls who participated in the 2015 offering of Fashion FUNdamentals demonstrated three key outcomes of girls' engagement in the program: (a) girls reported higher levels of self-esteem at the end of the program than at the beginning, (b) girls reported higher levels of self-efficacy in math and science at the end of the program than at the beginning, and (c) girls who perceived math and science as pertinent to or useful in everyday life were more prone to report higher interest in STEM at the conclusion of the program than at the beginning [19, 58, 59]. Key findings from qualitative analyses from the 2015–2017 offerings of Fashion FUNdamentals further enrich understanding of these quantitative results, revealing that participation in the program (a) expanded girls' appreciation for the value of STEM and the relevance of STEM to everyday life contexts, (b) moved girls toward increased self-acceptance, self-confidence, and self-esteem, (c) improved girls' problem-solving abilities and courage to learn by 'making mistakes,' and (d) developed a foundation for girls' future academic and career aspirations. Notably, immersing underserved girls in interactions with female faculty members, students, and STEM professionals in a university setting exposed girls to new ways of thinking about the role of STEM in diverse disciplines and careers and inspired them to attain a college degree and (possibly) to pursue a career in a conventional or nonconventional STEM field [59]. Taken together, then, quantitative and qualitative findings suggest that invoking a lens of fashion to explore the STEM disciplines can promote girls' academic and personal development [19, 58, 59].

2.3.3 Digital Youth Divas

Founded in 2013 and offered through the Digital Youth Network at DePaul University [61, 62], Digital Youth Divas is a hybrid, online and face-to-face STEM program designed particularly to address the needs of nondominant middle school girls who have not previously expressed an interest in the STEM disciplines [63, 64]. The program engages girls from underrepresented Chicago communities in design-focused engineering and computer sciences activities. Throughout the program, emphasis is placed upon immersing participants in narratives with nonstereotypical storylines, providing participants opportunities for interactions with racially-diverse female peers and mentors, and helping participants to call into question gender and racial stereotypes [63, 64]. Like Fashion FUNdamentals, Digital Youth Divas aims to bridge girls' existing interests with the STEM disciplines. Specifically, through their participation in Digital Youth Divas, girls are encouraged to develop STEM identities by interacting in face-to-face and online spaces to design, engineer, and re-imagine everyday objects (e.g., jewelry, fashion accessories, music) and activities (e.g., dancing, chatting with friends) using strategies of cooperative learning, critique, circuitry, coding, and making [61, 63, 64].

Digital Youth Divas has been offered in several formats (e.g., as an afterschool program, a one-week spring break program, and a two-week summer program), all of which incorporate four interrelated program components: (a) design projects, (b) narrative stories, (c) an online social network platform, and (d) a community of female and racially-diverse peers and mentors [61, 63]. Design projects are specifically developed to encourage interest among nondominant girls by engaging them in the construction of creative products (e.g., e-fashion, basic programming projects). Narrative stories introduce participants to various STEM/design-thinking challenges that prompt them to develop creative solutions through team-work; storylines deconstruct dominant stereotypes about race and gender. Within the online social network, participants engage with the program curriculum and the narrative stories, as well with one another, sharing their work and providing feedback to each other. Interactions within this context also allow participants the opportunity to construct their personal narratives and to 'try on' various STEM-related identities. Thus, the online social network represents a unique STEM environment that also supports girls' social and personal development. Finally, a community of diverse female peers and mentors is integral to all components of the Digital Youth Divas participant experience. Face-to-face female mentors share cultural background connections with participants and have completed program training but are not engineers by trade, whereas online mentors and program leads possess have formal expertise in engineering or computing as well as training specific to the program [61, 63, 64].

Since 2013, over 300 girls have participated in varied Digital Youth Divas program offerings [61], with evaluations suggesting similar participant outcomes across program formats [63]. Here, we summarize a qualitative evaluation of the pilot offering of the Digital Youth Divas after-school program [64] and a quantitative evaluation of a two-week summer program offering of the program on the DePaul campus [63]. The afterschool program was offered to a total of 17 girls at two public charter schools once/week for the spring semester. Observations of the learning sessions and in-depth interviews with participants revealed that, as result of their participation in Digital Youth Divas, girls experienced a sense of empowerment through the design/making activities. Additionally, findings suggested that the project narratives encouraged participants to persist in STEM challenges, lending a sense of authenticity to their efforts and fueling their interest in STEM learning. Girls invoked the narratives as platforms to dialog about diverse stereotypes as well as to envision varied (STEM, gender) identities for themselves [64]. The two-week summer offering of Digital Youth Divas was provided to 37 girls at a cost of $40 to participants and ran M-F from 9 am–3 pm. A comparison of assessments completed at the beginning and the end of the program revealed that participation in Digital Youth Divas positively influenced girls' understanding of STEM concepts as well as their confidence to take part in STEM activities. Engagement in the program also expanded girls' perceptions of 'who' ought to pursue STEM careers (e.g., to include people who are artistic) (cf, [16]). As such, findings provide evidence that a STEM program grounded in a narrative-based curriculum and committed to challenging stereotypes can support growth in nondominant girls' STEM interest, knowledge, and confidence, as well as their beliefs about inclusivity in STEM [63].

2.3.4 Connections to making

As noted, in varied ways, each of the programs highlighted here harnesses the potential value of making as an educational framework to support girls' learning in the STEM disciplines. Specifically, to varying extents and in differing ways, these programs incorporate components of making and the maker movement identified by Martin [28] as fruitful for supporting learning, including (elements of) the maker mindset, digital tools, and community infrastructure [28]. Most notably, at the core of each program is the framing of STEM learning as experimental play. For instance, girls are invited to be 'pharmacology sleuths,' to make ice-cream, to design their own textile prints, to create fashion accessories and products, and to engage with interactive stories, all while reinforcing their STEM skills. Here, then, STEM learning is cast as experiential and enjoyable because it is designed to be engaging and to build upon girls' interests and identities and/or to connect STEM learning to everyday, real-life contexts [28, 36, 42]. Fashion FUNdamentals and Digital Youth Divas, in particular, adapt the lens of making from an esthetic and personal expression perspective to entice girls to engage with STEM learning [24, 42].

As they 'make,' transforming materials into finished objects, participants in the featured programs employ varied digital tools, such as digital textile printers, body and foot scanners, and LEDs [28]. Open-ended activities afford girls 'free choice' in decisions about what form the objects they create will take—whether those objects be a bridge, an interactive story, or a craft/textile/fashion product [28]. Providing girls this sort of 'room to roam' creatively seems to build girls' self-confidence and sense of empowerment as makers and as STEM learners [19, 28, 53, 55, 58, 64]. Both individual and collaborative projects are undertaken in the featured programs, providing girls opportunities to exercise their individual agency as makers as well as to build their skills as cooperative learners and problem-solvers [28]. Incorporating collaborative, hands-on approaches to 'learning through doing' seems to promote an openness to learning through trial and error among participants in Fashion FUNdamentals [59]. This is of note, as STEM educators advise that learning through making mistakes will help the next generation 'test new ideas in messier ways' as they enter the digital age [65]. Finally, and importantly, central to the scaffolding of each of the highlighted programs is a commitment to (a) providing girls positive female mentors and role models in STEM (who, in the case of Digital Youth Divas, come from backgrounds similar to those of the participants) and (b) offering girls opportunities to connect with one another in face-to-face and/or digital formats, sometimes in contexts that extend beyond the duration of the program (as in the case of FEMMESConnect) [16, 28, 54].

3. Conclusion

As an active learning strategy—or a way of *learning by doing*—making encompasses a wide range of activities and draws from diverse disciplines. Its connections to computer programming, creativity, design, and engineering, in particular, position making as a unique and valuable vehicle through which to ignite girls' interest in STEM, build their STEM identities, and foster their confidence to pursue STEM education and careers [20, 21, 64]. However, access to making programs and makerspaces remains a significant challenge in leveraging the potential of making to stimulate girls' STEM learning. As previously noted, access to maker spaces is often constrained by structural inequalities, and especially for youth of color and young female adolescents, groups that have conventionally experienced limited access to extracurricular STEM educational opportunities, as well [20, 25, 26, 46]. Given their long-standing commitment to principles of inclusion, equity, and diversity as well as their resource rich environment (e.g., people, technologies, facilities), universities are an important stakeholder in expanding access to STEM education to all members of their community, including girls, through the development of outreach programs that incorporate components of making. As demonstrated in our overview, university STEM programs developed with the aim of facilitating access and equity in STEM learning among young girls may take diverse forms, may emphasize either conventional or unconventional STEM disciplines, and may incorporate elements of making in varied and unique ways. Key to the success of such programs in kindling girls' STEM interest, confidence, and identities seems to be incorporating activities (a) that leverage girls' existing interests, (b) that provide girls the freedom to define and express the self in creative ways, and (c) that offer girls opportunities to have "enjoyable" and "fun" experiences.

Although the girls enrolled in the university STEM programs reviewed in this chapter have evidenced positive outcomes, these and other similar programs are challenged to provide repeated "touch points" of contact with participants. To some degree, the capacity to build repeated touch points within a university setting is constrained by several factors, including (a) the time that faculty and student college student mentors can dedicate to such programming owing to their primary educational obligations and responsibilities; (b) the availability of university facilities, including makerspaces, equipment, and technologies; and (c) the availability of funding to support program development and operations.

However, in order to encourage girls to pursue STEM learning and STEM careers, continuous social and educational support through the K-12 years is needed [10]. A stakeholder approach that brings together university and K-12 educators—as well as other community groups such as students, parents, local government agencies, and local industry, particularly in the technology sector—may be particularly effective in addressing this challenge. Such an approach would enable varied stakeholders to collaborate in a joint effort to reach girls at multiple junctures across the K-12 educational pipeline by sharing expertise and resources across stakeholders (e.g., universities' sciences laboratories and makerspaces and K-12's educators' knowledge, skills, and time). For instance, presently, through Colorado State University's summer camp offerings, adolescent girls are able to participate in different STEM-based making programs such as Fashion FUNdamentals at the middle school level, Women in Construction Management at the early high school level, and SWiFT STEM camp (a computer science and coding program) at the upper high school level. If a coordinated effort were made to adopt a stakeholder approach to bringing together the directors of these programs with K-12 educators in the local school district, work could be undertaken to ensure bridge-building between university program content and the K-12 curricula, facilitating the dual aim of engendering within girls a passion for STEM learning through making and creating repeated touchpoints to support girls' mastery of key STEM concepts.

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Chapter 6

STEM for Sustainable Skills for the Fourth Industrial Revolution: Snapshot at Some TVET Colleges in South Africa

Moses Makgato

Abstract

Technological advancement is a major driver of the economic growth and has raised living standards enormously (though unevenly) across the globe. Digital technologies radically transform the structure of organisations and employment models, including teaching and learning. Youth and people who lack high-level technological and interpersonal skills are becoming vulnerable due to digital automated jobs. There is a need for targeted and strategic skills, and STEM that is responding to the changing technological world. The digital revolution and an increasing demand for designing and manufacturing are driving the growth of the creative sector, which extends from arts to science and technology and involves cultural creativity and innovation. Science, technology, engineering and mathematics (STEM) students should be equipped with designing and making skills for the twenty-first-century jobs. There is growing polarisation of labour market opportunities between high- and low-skill jobs, unemployment and underemployment especially among young people. Globally, almost 75 million youth are officially unemployed. This chapter present the driving forces for new jobs and skills for the future. The chapter also outlines the contribution of STEM knowledge and skills for digital literacy from basics to an advance level. The implication of digital literacy for the fourth industrial revolution is highlighted. The empirical part of this chapter presents results based on the investigation done on the vocational educational and training practices at three TVET colleges in one province in South Africa. The study focused on vocational pedagogic and didactic practices, workshop material and equipment for practical training, work-integrated learning and integration of theory and practice in vocational subjects. This investigation is a case study to gauge the extent of readiness of some TVET colleges for the fourth industrial revolution. The methodology of collecting data was questionnaires, interviews and observation. The participants of the study were students and lecturers. On the basis of these data, the paper determines the extent of readiness of TVET as well as CET colleges in the country. The paper recommends measures to position the TVET and CET colleges for the fourth industrial revolution.

Keywords: STEM, TVET, CET, fourth industrial revolution, digital literacy

1. Introduction

It is no secret that South African youth are facing massive challenges in terms of their education, employment and career growth. At the third quarter of 2019, South African unemployment rate has increased to 29% as compared with 26.5% in the first quarter of 2017. Youth unemployment has been inordinately high for many years in South Africa and is one of the country's major socioeconomic challenges [1]. Cross-country comparisons regularly affirm that South Africa's unemployment rates are among the highest in the world. In 2013, the youth unemployment rate was 63% of the youth labour force (3.2 million individuals). By international comparison, the ratio of youth to adult unemployment is fairly similar for other countries that are economically comparable to South Africa. However, the overall unemployment rate is far higher than in other emerging markets [2]. Of the 10.2 million individuals aged between 15 and 24 years, one-third are not in employment, education, or training (and are often referred to as "NEETs") ibid.

2. Material and research methods

This study is underpinned by the global and national literature in current trends on the forces that determine new jobs and skills for the fourth industrial revolution. This chapter presents the contribution of STEM education in upskilling and reskilling of people for the fourth industrial revolution.

This chapter also presents the empirical findings from three TVET colleges in one province in South Africa. The empirical part focused on vocational pedagogic and didactic practices, workshop material and equipment for practical training, work-integrated learning (WIL) and integration of theory and practice in vocational subjects. The empirical part of this chapter presents findings from a case study to gauge the extent of readiness in some TVET colleges for the fourth industrial revolution. The methodology of collecting data was questionnaires, interviews and observations. The participants of this study were students and lecturers, who were selected purposefully. The total number of students who completed the questionnaire was 119. These students were studying National Technical Education (NATED) and National Curriculum Vocational (NCV). This implies that there were 39 students for NATED N5 Industrial Electronics from College A, 31 students studying National Curriculum Vocational 1 Information Processing from College B and 49 students studying N5 Electrotechnics (NATED) from College C. NCV and NATED (N1–N6) courses are part of two main national curricula for TVET Colleges in South Africa. Each of these national curricula consists of several vocational subjects for various occupations. Interviews were done with the college lecturers who were observed in the classroom, and students completed the questionnaires. Observation of lessons of the subjects mentioned was done at each of the three colleges.

The questionnaire surveys were underpinned by the following sub-research questions:

RQ1: What are the vocational and didactic methods used in classrooms and workshops?

RQ2: What are relevant workshop materials and equipment for teaching and learning vocational subjects?

RQ3: How are the theory and practices integrated in the teaching and learning of vocational subjects?

RQ4: What partnership exists between TVET colleges and industries for WIL?

The results of this study helped to understand (1) the present vocational and didactic practices at TVET colleges, (2) the degree of TVET college readiness for the fourth industrial revolution and (3) the state of financial support for the reskilling and skilling of youth and adults for the fourth industrial revolution.

3. Literature review

3.1 Awareness of the forces for new jobs and skills for the future

Technological advancement is a major driver of the economic growth and has raised living standards enormously (though unevenly) across the globe. Digital technologies radically transform the structure of organisations and employment models. However, there is a growing fear of "technological unemployment" as technology become dominant in the economy. Such fears were experienced repeatedly through history in response to new technologies.

Technological change has reshaped the workplace continually over the past two centuries since the industrial revolution. The speed with which automation by digital technologies is developing today and the scale at which they could disrupt the world of work are largely without precedent. In the long term, technology has increased the productivity of workers and driven very substantial increases in living standards [3].

A 2011 study by McKinsey's Paris Office found that the Internet had destroyed 500,000 jobs in France in the previous 15 years but at the same time had created 1.2 million new jobs. This was a net addition of 700,000 or 2.4 jobs created for every job destroyed. Digital technology integration is having an amplifying effect on the institutional change. As new technologies come online and existing jobs are displaced, society will be under greater pressure to adapt and learn new skills. Jobs and employment models are continually changing with technology, owing to consumer preferences. These developments have been reshaping through the industrial revolution. New jobs, requiring new skills, are being created in manufacturing, mining, as well as the service sector industries. There is nothing new about continual change in the types of jobs people do and how they are done. Throughout history, governments, industries and society have been failing to make important choices about how to reskill human resources for the transition workforces into the future. One important difference about today's change is that we have many lessons to learn from. Many lessons have been learned about labour force transitions from the industrial revolution in the nineteenth century. In the knowledge economy, employability is directly related to relevant education and training [4]. Knowledge economy is based on knowledge and information [5], which forms the intellectual capital of organisations [6] and is a driver for growth and employment across industries [7]. Knowledge-rich industries, including professional, scientific and technical services, show rapid economic growth. Higher-skilled jobs are more complementary with technology and innovation, increasing productivity and earnings [8]. Patent growth is one of the indicators of technology innovation and growth in the knowledge economy [5, 9, 10]. These trends and projections highlight the importance of technical and vocational education for those who are yet to enter the labour market [11].

The advances of technology, digital connectivity and globalisation and the rise of new economic structures are creating new forms of jobs and employment models over the coming 20 years. We are witnessing a unique combination of forces that leads to much more rapid development and restructuring of labour markets in the near future than previously experienced.

As compared to previous technologies such as electricity and telephones, the rate at which new digital technologies are being developed and adopted is much faster [12]. The Internet and its accompanying technologies have been a game changer for many industries. They may be yet to unleash their full disruptive potential, owing to the establishment of the Internet infrastructure in both rural and urban areas. Unlike the first, second and third industrial revolutions, where the geographic limitation affected the flow of products and labour, the digital technology revolution (fourth industrial revolution) also known as internet change everything (ICE) has no geographical barriers. The new global Internet-enabled workforce employs new skills and competes with the local workforce, in just about anywhere in the world [13]. With the device connectivity, computing power, data volumes, e-commerce, social media use and other indicators of digital technology growth, we experience exponential growth both in terms of adoption and functionality. Employment models and jobs are significantly impacted by the connectivity. Most of the opportunities and risks associated with the "Internet of things" are yet to transpire. Essentially, the digital technology offers access to a whole new world of connectivity that is on 24/7 basis and that in itself is changing the way people work and live day to day.

IoT contains a variety of connected objects. The "Internet of things" is exploding. It is made up of billions of "smart" devices—from miniscule chips to mammoth machines—that use wireless technology to talk to each other (and to us). Our IoT world is growing at a breathtaking pace, from 2 billion objects in 2006 to a projected 200 billion by 2020. That will be around 26 smart objects for every human being on Earth. IoT is the combination of low-cost, low-power processors with "real-world" electronic sensors and wireless network connectivity being added to a wide range of electrical devices.

Mobile broadband and Internet access show the most rapid growth in developing countries. However, the divide between developed and developing countries remains vast, with mobile broadband penetration reaching 84% in the former and only 21% in the latter [14]. These digital divides need to be addressed in order to ensure that as many people as possible are able to access affordable, efficient mobile communication networks and the associated development opportunities, including employment.

The future of digital technological advancement holds exciting opportunities for the way we work, consume and interact and also poses challenges. Youth and people who lack high-level technological and interpersonal skills are becoming vulnerable due to digital-automated jobs. There is a need for targeted and strategic skills, education and training that are responding to the changing technological world. Supporting individuals in the application of transferable skills will be a key priority as we foster a sustainable and more productive economy. High-level technical skills in STEM education is required to underpin a successful economy. Technological digitisation and automation of our activities will have profound effects on the future labour markets. What are the deep-seated technological trends? And how can we prepare to maintain high standard of living in the country? The impact of these trends and the resulting skills must be better understood so that the appropriate STEM education and training is put in place to provide a prosperous and innovative economy for the emerging type of employees of tomorrow.

Increase of digital technology-automated systems is raising the complexity of tasks and the need for higher-level skills for entry-level positions. An increased STEM knowledge and skill levels in digital technology is imperative to access new jobs. Many middle- and high-skilled jobs are being automated. The consequence is the likelihood of a raised STEM skill training and education bar for entry into many professions and occupations.

3.2 Contribution of STEM knowledge and skills to digital technology jobs

The world of work is in a state of flux, which is causing considerable anxiety to everyone. There is growing polarisation of labour market opportunities between high- and low-skilled jobs and unemployment and underemployment especially among young people [15]. STEM education curricula at schools and TVET colleges have not kept pace with the changing nature of work, resulting in many employers saying they cannot find enough workers with the skills they need [16]. Education and training institutions should stop educating students for jobs and occupations that do not exist. The future requires workers to think creatively, work collaboratively, deepen their emotional IQ and integrate technology into everything they do [17]. It is unfortunate that even the best public and private schools still maintain an outdated focus on memorisation and following directions (ibid). To prepare students relevant to this technological era, schools must regularly make technology an integral part of their teaching, learning and assignments. Technology is becoming an even more common part of the workplace.

Science, technology, engineering and mathematics (STEM) knowledge is associated with 75% of the fastest growing occupations, innovations and wage premiums [15]. A technology- and knowledge-driven economy needs workers trained in science, technology, engineering and mathematics. The majority (70%) of employers in developed countries (e.g. Australia) characterise employees with STEM skills as the most innovative. About 75% of the fastest growing occupations require STEM knowledge and skills (ibid). The digital revolution and an increasing demand for designing and manufacturing are driving the growth of the creative sector which extends from arts to science and technology, creativity and innovation [18]. The new generation of workers often referred to as digital natives appears to be creative and looking for opportunities to express their creativity. Designing and making objects in STEM as creative thinking is expected to become increasingly important as a contributor to the national economy and the job market. Existing and new jobs are likely to require a creative approach to perform nonroutine tasks and solve problems, while future workers are likely to appreciate an opportunity to act creatively. STEM skills and knowledge are required for work in a growing range of existing occupations in the future and will also contribute to the creation of new professions within the digital technology era [16]. However, current trends demonstrate the lack of interest and poor performance in STEM. Furthermore, STEM subjects and related vocational courses and occupations (e.g. mechanical and civil) are still traditionally seen as more male-dominated work. There is declining trend in STEM knowledge and interest [19].This situation needs to be resolved to meet future workforce of vocational and technology needs. STEM education should provide employees, both males and females, with essential skills that promote innovation and productivity and support economic growth.

4. Data analysis and discussion

Student questionnaire results on vocational educational and training practices at three TVET colleges.

This section presents data collected from questionnaires administered to three TVET colleges. The data is presented in four tables. **Table 1** shows the biographical data of students at the three colleges combined. **Table 2** presents data on relevant workshop materials and equipment for teaching and learning vocational subjects. Data on **Table 3** provide students' views on the integration of theory and practice in the subjects. The data in **Table 4** provide information on the partnership between

Gender	*f*	%
F	31	26
M	88	74
Blanks	0	0
Age group		
18–20	39	33
Above 20	80	67
Blanks		
Total	119	100

Table 1.
Biographical data of students from three TVET colleges.

RQ1 Vocational pedagogy and didactics	*F*	%	*F*	%	*f*	%	*f*	%	Mean	SD
The VET pedagogy aims to enhance the students' capacity as independent thinker	7	6	10	8	101	85	1	1	2.77	0.59
The VET pedagogy is providing me with "a learning experience that is social, passionate and inspiring worker"	6	5	8	7	105	88	0	0	2.83	0.49
The emphasis is on "how" and "why" of the learning rather than the "what" only	9	8	47	39	57	48	6	5	2.30	0.82
The learning outcomes of the teaching and learning are very clear to students	6	5	17	14	96	81	0	0	2.76	0.53
The teaching and learning process is mainly by doing and reflection in vocational subjects	8	7	27	23	82	69	2	2	2.59	0.69
The teaching and learning engage students practically in performing a task through interaction	24	20	20	17	75	63	0	0	2.43	0.81
Sometimes I rely on sources other than my lecturer to know how some tasks are done	14	12	24	20	80	67	1	1	2.54	0.73
The teaching and learning utilise authentic hands-on practical activities that are true reflection of workplace activities	34	29	16	13	63	53	6	5	2.14	1.00
Vocational didactics focuses on competences and characteristics of a specific vocation or occupation	17	14	53	45	47	39	2	2	2.22	0.75
Relevant teaching and learning method is always applied for different types of vocational subjects	12	10	16	13	91	76	0	0	2.66	0.65

Table 2.
Vocational and didactic methods used in classrooms and workshops.

TVET colleges and industries for WIL. The details of data, analysis and related interpretations are presented below.

4.1 Biographical data of students from three TVET colleges

Table 1 presents data on the biographical data of students.

Table 1 shows that most students (88%) were male. It is not surprising, because the country is still going through transformation from the traditional male-dominated vocational education and training. The belief that mechanical, electrical

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Rating	Disagree		Neither		Agree		Blanks		Mean	SD
	f	%	*F*	%	*f*	%	*f*	%		
RQ2 Relevant workshop materials and equipment for teaching and learning vocational subjects										
I know the purpose of all materials and equipment available in this workshop	51	43	37	31	30	25	2	2	1.81	0.82
I consider that all materials and equipment in this college are able to prepare me for industry work	33	28	21	18	65	55	0	0	2.27	0.87
Lecturers are competent in the use of material and equipment that will prepare me for industrial work	27	23	25	21	67	56	0	0	2.34	0.82
The use of electricity-reliant equipment helps us to adapt quickly to current machinery in the world of work	21	18	19	16	79	66	0	0	2.49	0.78
I sometimes fail to complete practical activities due to the lack of adequate material	51	43	17	14	51	43	0	0	2.00	0.93
Sometimes I do use other materials and equipment other than prescribed in the task because the appropriate ones are not available	40	34	24	20	55	46	0	0	2.13	0.88
Sometimes I rely on sources other than my lecturer to know how some tools and equipment work	29	24	24	20	66	55	0	0	2.31	0.84
Materials and equipment that we use during practical are a true reflection of what we are taught during theory lessons	25	21	24	20	81	68	0	0	2.66	0.30

Table 3.
Workshop materials and equipment for teaching and learning vocational subjects.

and civil occupation is for male students is still prevalent at most TVET colleges but is slowly disappearing. Hopping [19] argues that STEM education should provide both males and females with essential skills that promote innovation and productivity to support economic growth. There is still high inequality in the country due to the previous dispensation.

It is common to find most students in the group above 20 years, because most of them are from post matric (grade 12—age 20) focusing on preparing for occupations for workplaces. These groups will be studying NATED programmes, while the younger ones will be studying NCV courses.

4.2 Vocational and didactic methods used in classrooms and workshops

The questionnaire results in **Table 2** show students agreeing to effective vocational and didactic approaches to the teaching and learning in the classroom. For instance, 85% of students agreed that “The VET pedagogy aims to enhance their capacity as independent thinker”. This is agreeing with [20] that educators will need a different pedagogy and skill during the fourth industrial revolution. Further, nearly one-third (63%) of students agreed that the teaching and learning engage them practically in performing a task through interaction. However, there was no complete agreement by students (39%) that vocational didactics focuses on competences and characteristics of a specific vocation or occupation. There were a considerable number of students (45%) who did not agree nor disagree on this indicator. The mean of 2.77, 2.83 and 2.66 shows an inclination towards and agreement in those indicators.

Rating	Disagree		Neither		Agree		Blanks		Mean	SD
	f	%	*F*	%	*f*	%	*f*	%		
RQ3 Integration of theory and practices in the teaching and learning of vocational subjects										
There are challenges that I face in developing the necessary skills and knowledge for social and economic development	21	18	23	19	75	63	0	0	2.45	0.78
The theoretical knowledge gained influences how I learn vocational subjects	9	8	27	23	81	68	2	2	2.57	0.70
The educational content is sufficiently relevant to the needs for qualifications in the actual vocations	7	6	30	25	82	69	0	0	2.63	0.59
The curriculum guides how to integrate theory of vocational subjects with practical exercises in workshops	30	25	29	24	60	50	0	0	2.25	0.83
The curriculum based on an adequate understanding of how vocational knowledge is constituted and developed	7	6	42	35	69	58	1	1	2.50	0.65
There is coherence between the classroom, the college workshop and the workplace and between subjects	23	19	48	40	47	39	1	1	2.18	0.77
Students are satisfied with the opportunities given by the educational structure and curriculum framework	31	26	21	18	67	56	0	0	2.30	0.86
Guidance is provided during placement periods	23	19	20	17	76	64	0	0	2.45	0.80
Lectures, assignments and work in the school workshop systematically related to placement periods	22	18	30	25	67	56	0	0	2.38	0.78
Theoretical knowledge is used to provide occupational relevance to work-related areas	7	6	24	20	85	71	0	0	2.61	0.71

Table 4.
Integration of theory and practices in the teaching and learning of vocational subjects.

4.3 Relevant workshop materials and equipment for teaching and learning vocational subjects

Table 3 indicated that more than half of students (51%) disagreed that they know the purpose of all materials and equipment available in the training workshops. Most of the students (65%) agreed that they consider all materials and equipment in the college to prepare them for workplaces. This is contrary to [16] who states that educational systems have not kept pace with the changing nature of work, resulting in many employers saying they cannot find enough workers with the skills they need. Further, unemployment rate in South Africa increased to 27.7% in the first quarter of 2017 from 26.5% in the previous period [1]. From the findings in **Table 2**, students seem to be positive about equipment and materials in the training workshops. The observations at the colleges investigated also do not agree with students' positive opinion about equipment and material at the college.

4.4 Integration of theory and practices in the teaching and learning of vocational subjects

At TVET colleges teaching and learning of vocational subject should focus more on practical skills. As a result the integration of theory and practice should be in the core of teaching and learning of occupational subjects. **Table 4** provides students' views on the integration of theory and practice in the subjects. Majority (75%) of students agree that there are challenges they face in developing the necessary skills and knowledge for social and economic development. Three quarters (68%) of students agreed that the theoretical knowledge gained influences how they learn vocational subjects. Similarly 68% of students agreed that lectures, assignments and work in the school workshop systematically related to placement periods. These results do not correspond very well with existing studies that most of the youth in the country are unemployed and that schools and colleges are busy training students for jobs that do not exist [1, 16].

4.5 What partnership exists between TVET colleges and industries for WIL?

Partnership with relevant industries and placement of work-integrated learning or work-based learning is an integral part of vocational education and training. For most of South African colleges, work-based learning is not adequately practised due to the lack or poor partnership with industries. This question sought information from students on the degree of partnership and work-integrated learning during their vocational education and training. **Table 5** shows that less than half of students (43%) agreed that various partnerships exist between TVET colleges and industries at regional and international levels. It is interesting that more than a quarter (33%) of respondents neither agreed nor disagreed. Nearly half of students (24%) disagreed that various partnerships exist between TVET colleges and industries at regional and international levels. **Table 5** also shows that half of students (50, 54, 51, and 55%) agreed on the importance of partnership in vocational education and training. However, there were a considerable number of students who neither agreed nor disagreed. This implies that partnership and WIL is lacking or poor at colleges.

Rating	Disagree		Neither		Agree		Blanks		Mean	SD
	F	%	F	%	F	%	F	%		
RQ4 What partnership exists between TVET colleges and industries for WIL?										
Various partnerships exist between TVET colleges and industries at regional and international levels	29	24	39	33	51	43	0	0	2.18	0.80
TVET colleges form partnerships with industries to ensure responsiveness to local and international community needs	25	21	35	29	59	50	0	0	2.29	0.79
These partnerships influence the successful labour market outcomes such as ensuring quick absorption of graduates into the workplace	28	24	27	23	64	54	0	0	2.30	0.83
Partnerships influence the successful labour market outcomes such as upgrading machinery and equipment	25	21	33	28	61	51	0	0	2.30	0.79
Partnerships influence the successful labour market outcomes such as improving supply of middle-level skills	20	17	33	28	66	55	0	0	2.39	0.76
Partnerships influence the successful labour market outcomes such as reducing skill shortages and mismatches	31	26	35	29	53	45	0	0	2.18	0.82

Table 5.
Partnership between TVET colleges and industries for WIL.

5. Interview results from lecturers

Interviews were conducted with lecturers of students at the three colleges. The participants responded to questions related to (1) vocational pedagogy and didactics, (2) equipment and materials in the workshops, (3) integration of theory and practice and (4) partnership with workplaces and WIL. Therefore the themes of results are organised in term of these four elements.

5.1 Vocational pedagogy and didactics and integration of theory and practice in the classroom/workshops

The lecturer teaching electrical engineering responded that there was no integration of theory and practice.

The researcher asked: "Is there any practical you do on your subject?"

Lecturer: "No, it's just theory".

The teacher says that there are no workshops for practical. The teaching is mostly based on textbook.

Lecturer: "I teach them theory most of the time, and the practical they must do on their own".

The type of practical the teacher was referring to was calculations of electrical quantities using calculators.

I asked the teacher the question: "Do you have practical?"

The *lecturer/teacher responded*: "No, I mean calculations".

The teacher who was teaching Computer Practice N5 in the same college states that students spend much time in the practical of the computer, because theory was too short.

Lecturer: "Our theory is very short so most of the time we concentrate on practical".

However, the teacher complained that the content of the subject she was teaching was outdated because it was never revised since 1999. It is not surprising why employers cannot employ most students from colleges because of this mismatch of knowledge and skills [1] [16]. This mismatch was also confirmed by the teacher as follows:

Lecturer: I am only concentrating on the textbook, for example financial management students they are doing computer practice they are doing calculations yet when they go to the corporate they come back saying what we teach them it's not relevant to their work place due to the system each company may use as individual. The teacher states that she requires continuous professional development because he/she is not a professional teacher.

For instance, the teacher said: "More training for me because I am not a professional teacher so I don't know how to deal with the behaviour of students".

At the third college, the lecturer who was teaching Electrotechnics emphasised that he was always bringing practical components when teaching, as a way of integrating theory and practice.

Lecturer: "Sometimes you see now in the class I do have machines. Even there you can check I do have machines. My subject is based too much on machines and other components of electrical. I do bring some, like conductors that I do have, whatever subject it requires based on the chapter which I'll be teaching".

The lecturer in this subject (Electrotechnics) also stressed the fact that the content is outdated, and it is going to be reviewed. The NATED curriculum taught at TVET colleges was introduced by the apartheid regime and has not being reviewed. [21] argues that too much bureaucratic red tape and unnecessary detail will retard technological changes in the country. There is great need to fast track TVET transformation in order to meet the needs of workplaces in skill provision. The existing TVET colleges are failing to produce skilled youth because of the bureaucratic red tape in terms of funding.

5.2 Partnership with workplaces and WIL

On the issue of partnership and WIL, the lecturer mentioned that she/he was not involved in that; however the teacher said that partnership is much relevant especially in the subject he/she was teaching because it is a practical subject.

The teacher responded: "No, I am not involved in that field, but I know sometimes companies offer our students learnership".

The lecturer mentioned that workplaces for students to do practical are very rare.

Lecturer: "Yes, and we don't have places that you can go do practicals".

The lecturers continues: no, no we need that, we need it and who ever can help us and the students would like it, they keep on asking me always, they say why we are not placed, and I got no answer. It is clear that these colleges do not have equipment and materials, because they do not do practicals.

5.3 Observation of training workshops

The study made observation in the practical workshops and during teaching. The observation schedules included (1) workshop/learning environment layout conducive for teaching and learning vocational subjects, (2) all material and equipment fully functional, (3) safety kits and utilities visible for all, (4) adequate working spaces provided around electrical power supply for normal operating and maintenance tasks in the workshop, (5) availability of materials to be used relevant for instruction and (6) natural and artificial lighting promoting effective functioning of practical lessons.

The above pictures show some training venues for students in the Electrotechnics and Automotive occupations, respectively. The materials observed that are used for practical are not corresponding with the latest technologies. For instance, most students are still trained using vehicle carburetor, while modern cars are using fuel injectors. It is not surprising that majority of youth trained from TVET colleges are not employable at most workplaces. Employers are complaining that the current education graduates are not work ready [21]. In a study by [21], in an interview, a manager uttered that education should "...give us a finished package" or "at day one be absolutely perfect". There is shortage of public/private training providers to provide knowledge and skills, education and training for the fourth industrial revolution such as IoT, AI, cloud computing, 3D printing and robotics/coding/programming [21].

A study by [22] indicates that one-third of industry experts in the USA had no confidence that education and training would evolve rapidly enough to match demands of technological advancement by 2026.

6. Conclusion

This chapter succeeded in presenting a review of literature demonstrating that rapid technological advancement is the major driver of the economic growth and has raised living standards enormously across the globe. From the review of literature, it can be concluded that there is a need for targeted TVET occupational skills, which are responding to the changing technological world. There are a number of recommendations made from the empirical findings presented in this chapter. It is concluded from the findings of this study that vocational pedagogy and practical skill training are not responding to workplaces and lead to high unemployment of youth. It is recommended that there should be massive upskilling and reskilling of TVET college teachers in various occupational fields. The findings also revealed that there are minimum or no practical activities at most of the colleges, hence no integration of theory and practice in vocational subjects. This study found that the curricula offered at the TVET colleges are irrelevant and require urgent review in order to respond to the current workplace. The teachers/lecturers at colleges require reskilling and upskilling to keep abreast with the latest technological development. Financial support from SETAs and related funders is required urgently to reskill TVET/CET college lecturers with fourth industrial revolution occupational skills. Short courses within occupational skills such as plumbing, welding, CNC programming, 3D additive manufacturing, robotics and IT are required at massive skills to combat unemployment, inequality and poverty. Bureaucratic red tapes and long procurement process should be removed if the country is serious about the fourth industrial revolution.

Although this study does not claim to be generic with the results, the empirical conditions can be found to be similar in many TVET/CET colleges in the country. More clinical studies are required at TVET colleges, as this study did not cover all colleges and their campuses in the nine provinces. The researcher acknowledges some good reform and transformation in some colleges, however very small, given the majority of youth with no relevant skills for employment.

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Chapter 7

Gender Equity in STEM Education: The Case of an Egyptian Girls' School

Mohamed El Nagdi and Gillian Heather Roehrig

Abstract

This chapter explored gender equity in STEM education within the context of an Egyptian STEM school for girls. An intrinsic case study design was used to explore the experiences of girls in STEM from a socio-cultural perspective within a critical theory framework. The participants were STEM school graduates currently enrolled in engineering tracks in higher education institutions in the United States. Though STEM fields, especially engineering, are stereotyped as male dominated fields, Egyptian girls at a Cairo single sex STEM school pursued further studies in STEM fields. Findings show that gender gaps in STEM fields in Egypt and girls' education and work decisions were deeply influenced by their childhood background, family education level, socioeconomic status, and idiosyncratic factors like self-efficacy and resistance. At the school level, teachers' support, challenging STEM curriculum, dynamic formative assessment, student-centered pedagogies, female friendly teaching approaches, and a positive school environment played a great role in developing Egyptian female students' potential to pursue STEM fields in higher education institutions.

Keywords: gender equity, STEM education, case study

1. Introduction

Gender equity in education, especially in science, technology, engineering, and mathematics (STEM) education, is a global priority [1]. For example, only 20% of bachelor's degrees in the United States were awarded to women in physics and engineering, with only 35% of degrees across all STEM fields being awarded to women [2]. Women's under-representation in STEM has been observed in 50 countries around the world, making it a global issue present in both post-industrial and developing countries [3, 4]. Research in this area has explored underlying reasons behind the gender gap in STEM fields through consideration of biological, social, cognitive aspects or career preference and initiatives designed to promote females' pursuit of STEM [2, 5, 6].

Most of the research in gender equity in STEM education has been conducted in the Western world, whereas in the Arab world, gender equity is primarily reported by international organizations such as the World Bank [7] from a developmental perspective. Gender equity in the Arab world—a diverse grouping of 22 countries in the Middle East and North Africa—ranks lowest in the world [8] and Arab countries have the lowest female employment rates in the world. The few women in male-dominated fields experience traditional gender dynamics, are promoted less, and have little access to decision-making positions [9]. The roots of the gender disparity in the Arab World are arguably related to (1) the patriarchal structure in the region, (2) dominant public sector employment and weak private sector employment, and (3) an inhospitable business environment for women because of the conservative nature of gender roles [10]. Within the Egyptian context, women have not exceeded 24.2% of the overall workforce, with even lower participation in the male-dominated field of engineering [10, 11]. Attempts to address this have been underway since 1990s, including the establishment of STEM schools which provide the context for this study.

Two public STEM high schools (one for boys in 2011 and one for girls in 2012) were established to provide an alternative to the existing traditional teaching and learning approaches in Egyptian education system [12]. This was considered a bold move towards ensuring equitable STEM education opportunities for both male and female students [13]. All graduates from the first STEM school cohorts have joined STEM tracks in higher education institutions inside and outside Egypt. These STEM schools have unleashed the STEM potential in Egyptian young people, male and female [12, 13], and thus warrant exploration into their success in motivating Egyptian females into STEM careers. Hence, this study was initiated and guided by the following research questions:

1. What were the experiences of the female graduates of the Egyptian STEM high school that motivated them to pursue STEM fields in higher education?

2. What were the underlying social, personal, and school factors that made these STEM experiences successful?

2. Literature review

2.1 Egypt and gender inequity in education

The Egyptian general Secondary Education (EGSE) Certificate is the official gatekeeper for higher education in Egypt. The percentage of girls passing the EGSE exams in 2016 was 92.3% compared to 87.8% for boys and in 2017 87.7% for girls and 84.0% for boys [14]. Yet female numbers in science and engineering in higher education do not reflect these scores. Further, a comparison between females joining engineering schools and those who take up engineering professions reveals a further gap between academic study and employment [11]. The share of women within professional and scientific fields in Egypt is among the lowest in the world [7, 15].

Family background and geographic differences all contribute significantly to these gender disparities [10] in a country where women are seen as fragile and unable to compete with men in jobs like engineering. Culturally, this type of work is seen as taking a woman away from family which is considered the appropriate role for women [10], inevitably reinforcing the institution of marriage as a permanent alternative to work [16], especially when husband has the financial ability to sustain the household.

2.2 Research perspectives on gender gap in STEM

Different perspectives have emerged as to what constitutes barriers to women in the STEM fields [5, 17, 18]. These perspectives are reviewed in the following section.

Some researchers argue that girls' and boys' interests are inherently different [18]; girls are more interested in issues to do with human health and well-being, whereas boys are more interested in things to do with technology and physics (1). Even within science, it has been reiterated that women with an interest in science are more likely to enter fields such as psychology and the biological sciences. Indeed, interest in physical science on the part of boys and biological and social sciences on the part of girls has been found in children as early as first grade [17].

There is conflicting evidence regarding gender and academic performance in STEM. From one perspective, research posited that women come to know things in ways different from those of men; men tend to consider facts in isolation, while women integrate them into a broader context and tend to start from a personal experience. Thus, traditional mathematics teaching that targets algorithms and emphasizes abstraction, logic, and certainty may impact females' achievement especially in mathematics [19]. Even those women who were extraordinarily adept at abstract reasoning were found to have a preference for starting from personal experience [19]. However, a meta-analysis of 100 studies found that gender differences in mathematics performance are small [20]. For instance, it was reported that while males scored significantly higher on college entrance exams in the United States, females obtained significantly higher grades while in college [21]. Girls are expected to perform better in mathematics if teaching builds on the strengths of connected learners, focusing on experience, conjecture, induction, creativity, and context [22].

Socioeconomic and cultural elements also play a major role in determining female students' attraction to STEM related fields [2, 23]. The dominating social and economic culture, as well parental influence, that can be overt or subtle, may have a great effect on female students' academic preferences [16]. Eight key findings that point to environmental and social barriers to female interest and pursuit of STEM fields were identified—chief among them are stereotypes, gender bias, and the climate of STEM departments in colleges and universities—that continue to block women's progress in STEM [2].

Stereotype threats are considered a major factor contributing to gender disparity in STEM [24]. A stereotype threat "refers to the experience of being in a situation where one recognizes that a negative stereotype about one's group is applicable to oneself" ([25], p. 5). Stereotype threats include the belief held by many pre-college women that they would be isolated in engineering tracks due to their gender and that they do not have a strong enough mathematical background to pursue an engineering career [24] arguing that stereotypes predict national gender differences in science and mathematics achievement, rather than simply a consequence of generalized national gender inequality. There is need for building a positive learning environment to enable female students to develop positive STEM identities that persist across K-16 and into STEM careers and dispel stereotype threats [23].

2.3 Pathways to improve gender equity

Confronting gender disparities in STEM requires efforts on several fronts: socio-cultural, personal, and school levels including fostering self-efficacy and improving the classroom environment to create a female friendly atmosphere to overcome stereotype threats [26]. At the school level, teachers need to change the way they give critical feedback; foster intergroup conversations among students from different backgrounds; allow students, to affirm their most valued self; help students develop a narrative about the setting that explains their frustration while projecting positive engagement and success to improve their sense of belonging and achievement [27]. In this sense, calls for girl-friendly instructional strategies are timely [28].

These strategies include making content relatable to everyday applications through societal connections and connections to prior experiences [22]. Participation in hands-on activities and extra-curricular STEM activities has also been shown to enhance girls' skills [18, 29].

Fostering girls' self-efficacy is a significant factor in improving equity in STEM [30, 31]. Self-efficacy refers to one's belief about their ability to succeed in a certain task [32]. Increasing self-efficacy can overcome the stigmatized stereotypes of women being perceived as not compatible for STEM fields [5, 24]. Integrating STEM project-based learning into the curriculum and providing female role models can enhance STEM self-efficacy and professional commitment to engineering [33, 34].

Research findings reported that the academic performance of friends of the same gender significantly predicted course taking in all subjects for girls [35]. Specific to mathematics and science, "the effects of friends' performance are greater in the context of a predominantly female friendship group, which suggests that such groups provide a counterpoint to the gendered stereotypes and identities of those subjects" ([35], p. 221). The creation of same sex learning environments is also responsive to what the American Association for University Women (AAUW) [36] refer to as indicators for gender bias in co-educational classrooms, both at the K-12 and higher education levels. American Association of University Women (AAUW) maintains that females have historically received less teacher attention than boys, feel less comfortable speaking out in class, face threats of sexual harassment in school [36]. These indicators suggest single-sex schools or classrooms as a solution to the gender gap in STEM. The National Association for Single Sex Public Education also indicates that girls in single-sex educational settings are more likely to take STEM classes as girls have more freedom to explore their own interests and abilities in single-gender classrooms [37].

However, there are conflicting findings concerning single sex educational experiences [38] that warrant further research. Both single sex and coeducational schooling can provide successes or failures depending on how these school systems are implemented, indeed "sex-segregated education can be used for emancipation or oppression. As a method, it does not guarantee an outcome" ([39], p. 189). In other words, the quality of the education provided in terms of professional well-trained teachers; well-equipped schools, and well-designed, engaging curriculum; and positive school atmosphere is the main factor for success in either system.

Based on the literature reviewed, it can be argued that girls are able to excel in STEM related fields when they are placed in a learning friendly atmosphere, where quality education is provided and social barriers such as stereotyping and gender bias are absent. Providing female friendly school environments, using dynamic formative assessments, STEM focused curriculum [40], working in a non-competitive, and in some cases same sex environment [38, 39] can be assets towards improved girls' performance, excellence and understanding of STEM related fields.

3. Conceptual framework

The nature of gender inequity in STEM can be conceptualized as an outcome of intersectional power dynamics between social, cultural and personal frameworks [41, 42] reflecting a recursive relationship between social structures and cultural representations [42]. Within this social critical theory framework, the commitment to justice liberates individuals from conscious and unconscious constraints that interfere with balanced participation in social interaction [42, 43] in an effort to analyze the constituents of the cultured context and replace them with emancipatory ideologies. Accordingly, knowledge generation and identity formation can be based on a critical reflection of the power relationships which are embedded in the structures and functions of society where society is structured by meanings, rules, convictions or habits adhered to by social beings [41, 43].

In spite of all the written documents, laws and codes of ethics that guarantee equity in all fields, the low representation of females in different male dominated fields might underlie, in addition the social intersectional power dynamics, the less-than democratic character of STEM occupations [44]. There is compelling evidence that gender roles are largely created and maintained in structured social order, with specific roles assigned to each group that reflect a myriad of cultural, social, religious, and political beliefs and boundaries [45, 46]. Davies [45] alluded to the subtle perception disseminated among family members and society at large that girls are looked upon as "fragile, weak, and powerless" ([45] p. 68), making a decision to pursue engineering as a career is a challenge to this social image reflecting different contextual barriers to such career choice [47]. "Resisting this prevailing pattern gender inequity, occurs on three levels: personal level; the group or community level of the cultural context created by race, class, and gender; and the systemic level of social institutions" ([43], p. 227).

4. Methodology

4.1 Context of the study and research design

The STEM high school for girls in Cairo, Egypt, along with another school for boys, were the first two model STEM schools in the country. The girls' STEM school was established during the turmoil and rising aspirations of January 25th, 2011 revolution. The STEM initiative in Egypt was supported by a grant from the United States Agency for International Development (USAID), with Education Consortium for the Advancement of STEM in Egypt (ECASE) leading the process of curriculum development, teacher professional development and technical support [13, 48]. As part of the project, the ECASE released quarterly reports on the development of all aspects of the STEM schools' projects including teachers and students' achievements [49]. The number of STEM schools has now expanded to 11, located in different Egyptian Governorates with hopes of having a school in each of the 27 Governorates [50].

The first two STEM high schools were boarding schools, with students being selected from across the country using a merit-based criterion. Teachers were selected mainly from the existing teachers in the Ministry of Education through a competitive process that included an online language exam, subject matter test, and interview with Ministry of Education officials [12, 13]. The language of instruction is English, while most of the students come from schools where Arabic was the language of instruction.

Students in the girls' STEM school experienced the same curriculum as the boys' school, including project based learning. The female graduates have been successful in terms of enrollment and achievement in the STEM fields. All the graduates of the first two cohorts—except for two who joined business administration—joined STEM tracks in higher education institutions. Around 70% joined science and engineering programs at universities inside and outside of Egypt. The other 30% joined medical-related fields, like medicine, pharmacy, and physiotherapy. Students participated and won prizes in science and engineering fairs at the local and international levels, encouraging more girls to follow on their footsteps, as evidenced by the large numbers of girls competing to join these schools and the number of girls applying for STEM schools outnumbering boys in 2017 [51].

The first author started working at the STEM school for girls in the second semester of its first year as a teacher of English as a foreign language. Subsequently, he took over the role of a coordinator of professional development for the teachers and supervising the students' capstone STEM projects completed each semester. This experience lasted for three consecutive years where he had built very good relations with students and teachers alike. This provided a rich understanding of the school context and familiarity for the participants in sharing their experiences.

An exploratory, descriptive intrinsic single case study design [52] was used as the purpose of the research was to look at the experiences of the STEM girls in its entirety including social, school, and personal aspects corresponding to the nature of an intrinsic case study wherein the participant, in this case the female STEM graduates, itself is the primary interest [52]. In this case study, the individual female participants represent the units of analysis. The study was reflective and retrospective in nature as the participants graduated from the school 3 years ago. This provided a robust design as the participants had a chance to reflect on the impact of their experiences at the STEM school on their learning at the university level.

4.2 Participants

Participants (see **Table 1**) were purposefully selected [53]. The criteria used for selection were (1) female graduates of the STEM school who joined engineering schools in higher education, (2) lived in the United States at the time of the study as the first author was there doing his doctorate, (3) came from different geographical locations in Egypt to reflect the different socio-cultural background of different locations in the country, and (4) from the first cohort of girls at the STEM high school to reflect both the challenges and success of the introduction of STEM schools. Selecting students living in the United States was a delimitation as a response to logistics reasons. Five graduates who pursued engineering at higher education in the United States were selected.

4.3 Data collection

Semi-structured interviews were conducted with the five participants. One of the interviews was done face to face, while the other four interviews were

Name*	**Where from**	**Parents' background**	**HE major**
Aida	Cairo	Father is an engineering professor and mother is in management position	Computer Engineering
Alia	Cairo	Father is an engineer	Biomedical Engineering
Fareeda	Delta	Father passed away while at elementary student and mother is a teacher and brother is an engineer	Chemical Engineering
Latifa	Delta	Father is a civil servant and mother is a language teacher	Computer Engineering
Muneera	Upper Egypt	Both father and mother are high school education level and all her siblings are medical school graduates or students	Biomedical Engineering

**Names are pseudonyms.*

Table 1.
The participants' names, geographical locations, family background and HE majors.

RQ	Sample interview questions
What experiences did the graduates of the Egyptian STEM high school have that motivated them pursue STEM fields in higher education?	How would you describe your experience at the STEM school? How was working with girls from different backgrounds for you? What was it like? What was special about the school's curriculum? Describe how were teachers' teaching approaches different? How was assessment different from those in your previous school, if at all?
What were the underlying personal, social, and school components that made these STEM experiences successful?	Tell me a little about your family? What is your father's occupation? Your mother's? What were your major interests before joining STEM school, literature, mathematics, science? If the MoE decided to build more STEM schools, what would they consider? Tell me a little bit about how you thought about mathematics and science in middle school?

Table 2.
Sample interview questions aligned with research questions.

conducted using Skype. Interview questions were designed to inform the research questions and address the different aspects of the conceptual framework of the study (see **Table 2**).

5. Data analysis

The interviews were recorded, transcribed, and coded. Content and relational inductive open coding was conducted vertically (for each participant) and horizontally (across the different participants) [54]. Next, axial coding was used to identify emerging themes. The data was revisited multiple times to make sure that the emerging themes and subsequent assertions were backed by the participants' words and perspectives.

An in-depth data analysis was used to synthesize the findings between the separate cases to understand similarities and differences among them [54]. These final themes were then connected to the theoretical and conceptual framework of the pertinent research on gender equity in STEM [2, 6, 23, 26, 43]. Ultimately, a contextualized intersectional argument depicting a layered pattern of supports and barriers for equity in STEM education in this case emerged.

5.1 Findings

In this section, cross-case narrative and analysis of the participants' unique experiences is provided. The themes that emerged from this cross-case analysis are discussed in depth providing an intersectional pattern of supports and barriers to gender (in) equity in STEM education in this study's context. **Table 3** portrays these emerging themes. The themes are categorized into three levels: family and social; personal; and school.

5.2 Emerging themes for the cross-case analysis

5.2.1 Family supports and barriers versus personal choices

The interaction between the social and personal power dynamics among the participants revealed a direct relationship between family bias and the girls'

Themes	Subthemes (codes)
Family and social barriers and supports	Parents' support Stereotype threats and (gender) biases
Personal aspects	Self-efficacy Persistence Resistance
School level supports and barriers	Challenging curriculum Dynamic formative assessment Teachers' support Student centered teaching strategies Positive school environment Extracurricular activities Single sex school setting

Table 3.
Supports and barriers for gender equity in STEM education that emerged from the qualitative interviews.

resistance. Three of the five participants in this study faced family biases against their dreams to be engineers. Fareeda's family members and teachers in primary and middle school adopted the perspective that "engineering is not for a girl." Fareeda's brother, who was an engineer himself, told her that "engineering is hard for me as a boy; what about you as a girl?" Likewise, Latifa, whose father was a civil servant and mother a teacher of Arabic, used to dream of being a doctor deeply affected by her mother's thoughts that "engineering is more like for guys, but medicine is very good for girls." Muneera's parents saw "engineering as having a lower status than medicine." With a middle-class family background with a high school education, Muneera's siblings, were either in or had graduated from medical school; "they [parents] wanted me to be a doctor and I wanted to be a doctor, too. Being an engineer didn't come to their or my mind at all."

Fareeda's teachers at primary and preparatory schools, all of whom were female, had the same perspective telling her that being "a doctor is good for a girl." Additionally, Fareeda's late father was hoping that she would be a doctor 1 day, so in addition other family and teacher preferences, she also wanted to honor her late father's wishes. Before joining the STEM school, Latifa was interested in mathematics which "has always been my favorite subject at school, even before STEM school, because for me it was very easy to do, like it's just simple, but I didn't like social studies because it needed a lot of memorization." While at the STEM school, she realized that as she was "better at math [ematics], it only makes sense if I become an engineer." When she decided to major in mathematics in high school as the pathway to engineering, her mother was initially upset. However, she did not press Latifa since she trusted her choices; "my mother believed in me."

Fareeda was able to confront the family and social bias with high degrees of self-efficacy, resistance, and persistence. Fareeda insisted, now "I see myself as an engineer and I will be an engineer." However, while at the STEM school, she decided to join the science major as this was the path to medical school in the Egyptian system, whereas entry into engineering would have required her to major in mathematics in high school. Her scores qualified her to join the school of medicine, however, she told her mother and brother while she realized their dreams, but she wanted to pursue her own dreams and instead applied for an engineering school in the United States, where she was accepted with a scholarship. She recalled, "They did not object this time. And my brother started to support me in my new adventure." Latifa followed Fareeda's suit, her parents became "so proud of" her and started to look at her as "an idol [model]" for other students to follow after she followed her passion for engineering. Interestingly, this did not prevent Latifa's mother from occasionally reiterating her wish that her daughter had chosen "the biology major and then she can become a doctor." Muneera also decided to break the family norm and become an engineering major. Yet she faced huge opposition; she had to join school of medicine for one semester before the call for engineering became irresistible. She joined a school of engineering in the United States after being accepted for a scholarship to fund her studies. Muneera's parents could not accept the idea that she would be an engineer and as Muneera reported "They still don't like it."

On the other hand, Aida's parents were supportive of her choices. Aida's father, who received his PhD from the United States and is currently an engineering professor, and her mother, who holds a managing position in a big company, "encouraged [her] and said let [her] try and discover things on [her] own." Prior to attending the STEM School, Aida attended a school where mathematics and science were taught in English, unlike other public schools in which this was done in Arabic. This was an asset for her in the STEM school where instruction was all in English. However, earlier in her primary and middle schools, she was more interested in "sports." Later, she discovered that she was good at mathematics; "I do calculations fast, and understood mathematical problems, but I did not imagine spending my life doing that [dying mathematics]." She became interested in "the value of education and especially engineering' only after witnessing the January 25th revolution and understanding how Egypt needs more educated people, scientists, and engineers to change its status quo. Aida believed that her study and career choice was not only affecting herself, rather "education especially engineering will help improve our country in the future" and that as an engineer she would "have a bigger impact than just like being a politician, architect, or doctor."

Likewise, Alia's father, being an engineer himself, "pushed her forward." She stated, "my parents were really encouraging and whenever I was in doubt. They were pretty supportive. I don't think they had any negative feelings towards STEM school at all." Her favorite subjects were mathematics and science which "were not challenging for me at all, what was challenging was the memorization-based subject like Arabic and social studies."

5.3 School level supports and barriers

5.3.1 STEM school experience and extra-curricular work

The different atmosphere, school culture, curriculum, relationships and assessment systems at STEM school provided a new opportunity for the participants to unleash their STEM potential beyond expectation. Aida argued that the STEM school changed her view about education as not just "buildings where students go to learn subjects like math and science" to the view that education is "about changing our way of thinking." Alia considered her STEM experience as "a very good one that [she is] grateful for being part of it." She maintained how the STEM school experience made them "independent [learners] in terms of that we had to self-learn, think, collaborate, and create … and come to class prepared to present." In her opinion, this was "interesting as it was student centered and taught us teamwork." Along the same lines, Latifa considered her STEM experience as "the greatest thing that happened and will ever happen in my life and I'm not exaggerating." It helped her to become "a good learner and a researcher." She stressed the perspective that the things she learned in STEM school would not have been possible in any other place: "I learned teamwork…how to talk with different people who have different perspectives and everything literally everything …all that I learned in STEM school way practice and [with] teachers' guidance." The school as a boarding national school was a mini cosmos. Through their experience with girls coming from "different parts of Egypt with different cultural backgrounds" in Aida's words, they gained a lot of experience dealing with people from different backgrounds which was "very helpful for her life in college in the United States."

Fareeda greatly valued her experiences at the STEM school. The teachers, in her view, were "like our parents" and "they were caring for us and tried to help us the most." She cited the example of the physics teacher when she talked to him about "her dream to be an engineer while [her] family wanted [her] to be a doctor', he advised her to 'follow [her] dream as [she] won't excel in a thing [she] doesn't like." Aida described the teachers as "very friendly even at the moments we made sit-ins and called for reforms to make our school better, they backed us." She went on to say, "they escorted us in our journeys outside the school looking for materials for our projects, and meeting with other experts in different places." She added, "they helped us to find new ways to get information, they used different teaching approaches like discussion." Latifa remembered how teachers were careful to warn students that "being different [as STEM students] does not mean being better than anyone else we're all good in our own unique ways." She maintained how the teachers used different teaching approaches: "some let us prepare materials and present them and they gave us comments and guided our discussions." Muneera also praised her teachers as supportive using "different strategies, but the majority helped us to be independent learners. I can depend on myself now at college if I don't understand something." In some classes, learning "was completely student centered where we did the entire presentation and the teacher was supervising us and only corrected us when there was something wrong."

However, all participants were concerned that "the teachers needed more training and professional support in STEM," especially with regard to assessment as "we were, not trained enough to answer the kind of questions we faced in the final exams." Latifa alluded to the need for teachers' readiness stating that "if teachers do not know or do not understand the [STEM] system, that would be a big problem for students because if students don't understand what the system is, teachers should know because they're supposed to teach students how to do things."

All of the girls valued the challenging and rigorous curriculum. For example, Aida stated, "the curriculum was so challenging with college level material" citing the different modes of assessment used at school as very conducive to learning. As a result of the challenging curriculum and assessment, Aida "had [knowledge] about nearly all the topics in my freshman year in classes like physics and calculus." Because of the college level content at the STEM school, Latifa was "tested out of calculus 1, 2, and 3 [because] most of these topics I covered in high school and also like physics one and two and chemistry one. I had all these topics [covered] in high school. Now I'm in physics 3 and I study some topics about waves and resonance and I remember how I used to watch videos explaining these topics in high school." She added that other things like "presentation skills and collaborative work [she learned at STEM school] were very helpful at college level." Alia noted that "the curriculum was very different from regular schools in Egypt and challenging." She found the college level material very helpful and shared that when she went to college, she "found many things especially physics and math I had covered in STEM school… and the way was taught it was special."

What was unique about the curriculum in Latifa's thought was the idea of not being restricted to text books; "you can understand the learning outcome from different references: the internet, teachers, colleagues." The curriculum at the STEM school was "more open" in Muneera's terms. She argued that "in subjects like biology and chemistry at the school I had the opportunity to dig deeper into the things I was interested in and I really appreciate that." That helped her a lot at university but "this openness was not good all the time. In some cases, it was not very straightforward [clear]. The goals of the curriculum or what do we have to learn after studying this subject were not clear."

For the capstone, for instance, Muneera mentioned that "each group was required to submit the following: a prototype or model of their solution, a scientific poster of the whole project, the project portfolio, and do biweekly journal reflections." Alia also mentioned the capstone project as "pretty challenging but also very useful in terms of helping us to acquire more knowledge, research skills, such as problem solving and technical skills like for creating the prototype, not to mention enhancing presentation skills." Latifa thought that the capstone projects were "the biggest point of the learning in STEM I guess… how we were supposed to deal with real-world problems and like find practical solutions for them. That was big." This was initially challenging for her as she was not used to this approach to learning and also that the teachers were learning this new system alongside the students.

In Aida's words, assessment was "different and difficult" with a "final exam each semester which accounted for 30% of the final grade where we worked collaboratively to solve one of the grand challenges of Egypt following the engineering design process." This was completely different from the mainstream secondary schools where grades were based solely on traditional final exams. Assessment, however, was challenging as it was completely different to traditional schools and "there were no direct questions because you have to think. You don't have to memorize …they were super challenging the first 2 years." Muneera described assessments as "checking understanding not checking memorization." Challenging as it was, assessment was more manageable and conducive to learning than "memorizing a book from cover to cover and then forget everything after the exam is over." Alia noted that the "assessments were different from the ones they had been used to, but we could eventually answer most of the questions." She found the college level material very helpful and shared that when she went to college, and "the way it was taught was special."

As learning dose not only happen inside the school premises, out of school extra-curricular work was seen as an integral part of the STEM school experience. The school provided different civic engagement opportunities with several organizations that gave students opportunities to visit universities and research centers to discuss scientific and engineering ideas. Muneera, for instance, was interested in chemistry outside of school and she used to "interact with those responsible for the chemistry Olympiad. They were faculty from universities." In addition to her work in the capstone and extra effort needed to finalize projects she "visited a lot of universities and interacted with professors there." Fareeda viewed engaging in different out-of-school activities and field trips as one of the greatest assets of the STEM school. She described the International Science and Engineering Fair (ISEF) experience as the "best thing that happened" to her in the STEM school. She learned a lot from that experience, in addition to winning the first award and participating in the United States international competition and winning the third place in their category, she learned "group work, presentation skills," and how to defend her ideas "in front of Nobel laureates." Latifa described her participation in a programming camp as a great learning experience: and "in the second year of high school I participated in Intel ISEF competitions and science fairs with EEE science fairs with the capstone project."

The research work required of students at the STEM school also pushed them to seek support outside the school walls. Aida recounted, "when I was in school, I worked on a project with the physics department at the American University [in Cairo]. I also went to Cairo University, and different [other] universities for school [projects] that helped me understand how research is done in university." Aida thought that these activities were of great value in her college level studies. Alia mentioned visits to "different universities and research centers and talking to professors about their projects" as reinforcing their STEM identity as they were "able to ask questions and discuss our work in a free way." Alia described the physical work they used to do build their projects prototypes; "in addition to engineers and professors who helped us in designing our [capstone projects] prototypes, we also sought the help of technicians like plumbers, carpenters, electricians to build certain parts of these prototypes."

Among the challenges faced by two of the participants (Muneera and Fareeda) was studying engineering while not being a mathematics major in high school. Muneera said it was a challenge at the very beginning but she added "I am doing very well in math now" and that the skills from the STEM school rather than content were the reason as, "now [at college] when I am stuck in anything, I can teach myself… I do not need someone to teach me…I can go find books or the internet, or any way to understand so I really think this was great from the school. I learned how to work in a group, though I speak different [foreign] language [with accent] I had the strong personality to face challenges… I had learned a lot how to deal with people." Alia argued that the experience at STEM school was invaluable in terms of helping them address any academic challenges because it helped her to be "an independent learner and know how to collaborate." On a personal level, she felt "it [STEM school experience] made me more confident and made my first years at college easier."

5.3.2 Single sex school setting

Being in a single sex school was not a new thing for almost all participants who come from Egyptian public schools. The general rule is that starting from grade seven most schools are segregated except for a certain track called "distinguished public language schools" in which mathematics and science are taught in English. Fareeda was a staunch supporter for single sex STEM schools as long as "they provide quality education and have similar teachers [to our school] and [similar school] environment." She argued that the female students "felt more comfortable" and had "the chance to work together freely without pressures, to compete in the female way to excel." She concluded, "it was a great experience all over. We worked together in a friendly way." Aida thought that single sex schools are "good, but they need more planning." If she were to choose between a co-ed or a single sex school, she would "choose a single sex school because the friendly atmosphere developed at the school made the students closer to each other in a way you can't find in another school." Along the same lines, although Alia initially stated that she "did not have a preference" for single sex versus co-ed schools, she "would choose the single sex school just because we created a community in which we lived together as sisters, it was kind of empowering." Therefore, if she were given the choice, she "would definitely go for single sex schools."

On the other hand, when asked about the single sex learning experience, Latifa was vocal in resisting that type of schooling. She said, "I think it would be better if both sexes were in the same school because I believe that this system and the way of thinking will be more inclusive of the two ways of thinking [male and female]." Latifa posited the reason behind the fact that girls' school "was relatively better at getting like high grades, while they [boys] win more robotics competitions and programming and like the technology stuff" is due to "a natural difference between the two [genders] in terms of foci and interests."

Muneera said, "if I went back I would prefer mixed schools." She had a hard time adjusting to the coed nature of higher education. All of her pre-university education life, including the STEM school, was single sex. Therefore, her ability to communicate with people from both sexes was affected by this long education experience. She explained "it was kind of the challenge when I came here. At the beginning I could not deal with guys. It was hard because I didn't have experience. I did not go somewhere else. I was all my life in that single sex school system." However, her experience in the STEM school pushed them "to build the environment where we're supporting each other and learning from each other as different people coming from different backgrounds."

6. Discussion

From a cross-case perspective, a multilayered pattern of the supports and challenges [47] that impact gender equity in STEM education in the Egyptian context were delineated (see **Table 3**). The intersectional nature of the educational and sociological phenomena [41–43] is clearly reflected in the journey of the participants in this study. The participants endeavor towards STEM fulfillment reflects the power dynamics and relationships which are embedded in the structures and functions of society where society is structured by meanings, rules, convictions or habits adhered to by social beings [42, 45, 46]. As a result of the data analysis, the underlying mechanism of factors that support or impede girls' pursuit of STEM tracks show complexities of the phenomenon of creating gender equity, both broadly and especially in the Egyptian context. This is clearly manifested in the emerging themes from the data analysis (see **Table 3**). The intersectional pattern includes the impact of the power relationship of the socio-cultural, educational, and personal aspects.

For instance, the existence of stereotype threats and biases [27] was salient in most of the participants' experiences. However, this was diminished by both factors at the personal and school levels epitomized in the girls' resilience and the supports they received through their experiences at the STEM school. The girls did not concede to family and social pressures; they pursued their own dreams. In their emancipation journey, they showed high degrees of persistence, self-efficacy, and resistance to the social norms and stereotype threats at the family level and the immediate social network [42, 45, 46]. In spite of the challenges they faced, the girls were able to navigate through this experience and benefit from it in their higher education engineering institutions.

In addition to the intersectional nature of the socio-cultural phenomenon of gender equity in STEM, these cases present a clear example of how gendered roles are created at both the social and family level [42, 45] and how they can be disrupted. One way to challenge such fossilized gender roles either explicitly or implicitly, especially in the absence of social collective effort, is through consolidating personal traits like self-efficacy and persistence [30, 31, 33]. This is apparent in girls' defiance to the commonly accepted stereotype that it is hard for girls to be engineers. There seemed to be a strong relationship between the degree of bias and the level of resistance on the part of the girls; in the cases where gender bias was explicitly reiterated, there was markedly higher degrees of resistance to such stereotype threats [27, 42]. However, to address gender inequity in STEM, more work at the social level and at school level is required [6, 29, 34, 44].

The school and teachers provided additional support to the girls' personal resilience. All participants referred to factors at the school level that were effective in deepening their interest in STEM, especially engineering. At the curriculum level, one of the common features was rigor and challenge. Moreover, at the assessment level, participants agreed that assessments were not checking memorization; they were checking understanding which has helped them in their higher education institutions. Not only did the participants refer to the challenging curriculum but the way that curriculum was delivered. The primary support came from the girl-friendly pedagogies they encountered at school. They referred to quality teachers utilizing student-centered approaches to teaching and learning, linking learning to real-world situations, group work, peer teaching, providing opportunities for students to increase their interest in STEM, linking content to prior experiences, providing first-hand experiences, encouraging discussion and reflections of the social importance of STEM fields, engaging students in collaborative learning, and a safe learning environment which all concur with research concerned with bridging the gender gap in STEM fields [6, 23, 26, 28]. This was documented in the ECASE reports as early as 2013 [47] in which it was noted that teachers have improved considerably in maintaining collaboration and adopting student centered pedagogies in their teaching [47]. Teachers were also viewed by all participants as supportive, encouraging and caring being viewed by most of them as "parents", though in almost all cases, students referred to the fact that teachers were still in need of more professional development. Research shows that quality caring teachers' support is crucial for a female equitable STEM experience [18, 22, 23, 29, 36].

Although there was variation of perspectives around the idea of single sex schooling, there was consensus that it provided a safe, comfortable environment for learning where collaboration and minimized competition was present. However, from the input provided by the participants, single sex school experience in itself and by itself was not a guarantee for gender equity learning experience in STEM [36, 38, 39]. In two cases, the outcome of the experience was not positive in the long term. It was hard for some of the girls to adapt to an environment where they had to deal with male and female students together in an academic environment. As a result, they felt frustrated at certain points for not being able to socially adjust to a coed institution environment though they were academically well prepared and maybe over prepared to these institutions.

The tension between providing a female-friendly, safe, and comfortable environment for female STEM students to work in; and at the same time nurturing the skills of being a part of a wider society was problematic. There is a need, therefore, for a balanced educational situation where girls are provided with the safe environment to learn and at the same time get involved in a socialization process that prepares them to the college level where a coeducational setting prevails both inside and outside Egypt [1, 3, 13]. Indeed, in the new STEM schools in Egypt, girls and boys attend the same school with classes inside the schools segregated by gender. Though this decision was made for economic reasons because it is hard to build a separate STEM school for each gender in each city, it can be one way to alleviate the tension between providing the female friendly safe environment while helping consolidate the socialization process that they will need later on in their academic and professional life.

7. Conclusion

Gender inequity in STEM in Egypt is a complex issue. While research denotes different reasons that would influence a girl's preference of an education pathway, the education and career choices of the participants in this study were deeply influenced by their family and community [47]. With the socio-cultural aspects in the background personal aspects like self-efficacy, resistance, and persistence play a great role in students' decisions to pursue STEM fields [24, 25]. As indicated in the literature, girls experience stereotype threat throughout their schooling related to the pursuit of a STEM career. In Western countries, these biases are often implicit and experienced as micro-aggressions [3, 4], however, in the Arab world, girls experience explicit and direct bias from family and society [10, 11]. Thus, the government stance of providing STEM schools for girls is an important statement to the community that girls can be successful in STEM.

Without effective and equitable school settings factors at the personal and the social level cannot have such deep effects on the girls' free career and educational choices. School level factors like curriculum, positive environment, female friendly instructional approaches, teachers support are key factors as shown by the girls' experiences in the STEM school [29]. Moreover, success in post-secondary STEM degrees is strongly influence by students' high school preparation, particularly in mathematics [33, 55]. Thus, it is important that girls receive the same level of high school STEM preparation so they are prepared for success in college. All of the girls indicated how well prepared they were for academic success. Equally important, is that the school experience fosters girls' interest and STEM identity through using a female friendly approach to teaching [23, 55].

With the different model of teaching and learning at the girls' STEM school in Cairo, the girls had the opportunity to unleash their STEM potential. This emancipatory effect of the STEM school experience has not only increased the girls' persistence and resistance to the gender bias and stereotype threats concerning STEM fields as male dominated but unleashed the girls' social and transformative potential towards building a more equitable society.

It is, therefore, recommended that much effort at both the academic and social levels is needed in order to create an environment where girls have an equal opportunity to study and excel in STEM fields. These recommendations include embracing a female friendly instructional paradigm while adopting a school system where girls are provided safe space for practice, competition, collaboration and ease of communication with others. Higher education institutions should be providing a more flexible admission system similar to that found in the United States and Europe giving access to students from different tracks at high schools to be admitted to their colleges of preference based on their interest and aptitude as some of the participants in this study applied to colleges abroad because the admission system in Egypt public universities would not allow a student graduating from high school with a science major to enroll in the school of engineering. Finally, at the social level, combating negative stereotyping is a necessity for building a sound education system for all. This is a long journey where a lot of work is needed in schools, homes, and media level. Therefore, there is a need for moving forward from the dictum concerning equity to real actions.

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Chapter 8

A Theoretical Framework for Implementing STEM Education

Vongai Mpofu

Abstract

Globally, strengthening Science, Technology, Engineering and Mathematics (STEM) education is recognized as embedding solutions to many societal problems like the depletion of natural resources and issues related to climate change. The recognition of STEM disciplines as economic drivers motivated the initiation of STEM education in both developed and developing nations. This is based on the thinking that an effective STEM education is a vehicle for developing in students the much desired twenty-first century competences. Yet, its operationalization has remained a great challenge in many nations. In most nations, educators lack a cohesive understanding of STEM education and are also deprived of an easy-to-understand STEM education framework that informs classroom practices. This chapter proposes a practical theoretical framework that nations may adopt and/or adapt for their STEM education to be successful.

Keywords: classroom practice, STEM education, STEM educators, theoretical frameworks

1. Introduction

Today, it is indisputable that Science, Technology, Engineering and Mathematics (STEM) are strong drivers of competitive national economies. Thus, throughout the world, nations are busy investing in STEM with the hope of grooming innovative minds to spearhead the development and sustainable growth of their economies. In education, strong STEM programmes are regarded as critical in developing students with twenty-first century competences (knowledge, skills and values) [1]. Twenty-first century competences including creativity, problem-solving and entrepreneurial are prerequisite students' further studies in STEM areas, their taking up of related careers and ventures into entrepreneurship and inventions [2]. In this regard, STEM classrooms require teachers who hold knowledge and pedagogies associated with different STEM disciplines and who would be able to construct new identities within their nation and school contexts [3, 4]. The economic development foundation-laying goals for STEM education are quite clear in literature. With all of the possible benefits of STEM education, it becomes imperative to ascertain that teachers teach STEM effectively [5]. Yet, quite often nations introduced STEM education void from context-specific theoretical frameworks and standard operating procedures (SOPs) to guide its understandings and implementations [6, 4, 7]. Logically, the success of STEM education endeavours is largely underpinned by well-defined national conceptions, theoretical underpinnings and SOPs of STEM education. Yet, in many nations, STEM teaching has been left to individual teachers

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to figure out what it entails and how to do it. The need for nations to clearly define theoretical framework for STEM integration remains [8] and cannot be overemphasized (Lederman & Niess, 1998).

Despite the increasing attention to STEM education worldwide, its stakeholders in particular educational institution managers and classroom practitioners are still grappling to come into terms with what constitutes STEM education and how it can move to classroom settings [9]. No clear-cut answer to these issues can be discerned in the literature and discourses among STEM-related communities of practice. Research findings that STEM education is failing in many nations can be explained from the non-available answer to this question. This problem is aggravated by a variety of STEM education frameworks (Berlin & White, 2010) which often lack consensus of what STEM and STEM education entail. For example, in Zimbabwe, the Primary and Secondary Education Ministry fails to agree with that of Higher and Tertiary Education, Science and Technology on the meanings of STEM education and their implications to its implementations [10]. Currently, Zimbabwe still does not have a clear and accessible national STEM education framework. An obvious and immense need for stakeholders to agree on what STEM education is and how it is to be introduced in educational settings can also be drawn from studies conducted in Turkey, Egypt, and the United States of America [11].

The main argument of this chapter is that in order to break the vicious circle of STEM education reform failures, academics need to examine and consequently collate different theoretical frameworks into easy-to-understand and easy-to-implement practical approaches. Different nations then can adjust such frameworks to their contextual needs. The chapter first discusses the Qualitative-Philosophical methodology adopted to develop the Science, Technology, Engineering and Mathematics Education (STEME) theoretical framework. Second, four approaches selected from literature and from which STEME was constructed are examined in turn. Third, how the theoretical framework was constructed and how it describes STEM education are presented and discussed. Fourth, the chapter discusses the practical applications of STEME model to translate STEM education into a living reality. The chapter ends with a final word after conclusions and recommendations.

2. Qualitative-philosophical methodology

STEM education literatures were Qualitative-Philosophical (QualPhil) studied to develop a STEME model this chapter proposes. QualPhil is a pragmatism-grounded approach that blends qualitative and philosophical research approaches. Pragmatic perspectives untangle epistemological boundaries in knowledge production through the mixing of approaches that are deemed relevant and fitting to the purposes of the study. The knowledge on STEM education was drawn from different sources and perspectives in literatures, and ongoing research works with students under my supervision in STEM education. The philosophical angle guided the synthesis of multiperspectives on STEM education done through the deductive and inductive interrogation of literature grounded in qualitative approaches [12]. The chapter rigor was enhanced by not only broad literature scope drawn across STEM disciplines but also frequent peer debriefs with academics and students doing postgraduate researches in STEM disciplines and STEM education. Procedurally, three phases were iterated. First, the study was informed by three years of student project work in STEM Education. The critical supervision of works in six students to completion phase in Zimbabwe provided insights into the theoretical origins of the conception and implementation of STEM education problems. In the second phase, 10 articles from conceptual and empirical credible sources were selected and analysed. Finally, the STEME model was developed through linking main categories (themes).

3. STEM education

Different STEM approaches have been adopted in different education contexts even within the same nation [4, 13–15]. Research reveals that this is the main source of confusions and misconceptions/misunderstandings of STEM education among teachers [14]. These confusions and misconceptions are ripple effected by Many other barriers to STEM education [16]. Four approaches that premised the development of the Science, Technology, Engineering and Mathematics Education (STEME) theoretical framework are described. These are pathed, integrated, continuum and STEAM (Science, Technology, Engineering, Art and Mathematics) education.

3.1 Pathed STEM education

The four pathways to STEM education suggested by this framework are isolated and independent (S-T-E-M), duet (e.g. SteM), one into three (e.g. E S-T-M) and all four infused (STEM) approaches [17].

The separatist or silo approach is also discerned in the literature as a traditional approach that holds the isolated instruction of each individual STEM subject [18]. Some symbolize this way of teaching as S-T-E-M to draw attention to its independent subject nature with no to minimal or integration. In schools, this approach manifests as traditional disciplinary list of school subjects like science (chemistry, physics, biology, etc.), mathematics, technology and engineering. It becomes a curriculum movement in that it emphasizes that subjects like technology and engineering which were largely excluded in the school curricula be included. The approach's established history and philosophy of classroom practices currently ground the STEM educators' (teachers in high schools and universities' lecturers) discipline-based training. Teachers informed by this approach tend to teach for subject matter understanding and enhancement of student achievements [19]. They value and conserve their specific knowledge domains [19]. Furthermore, S-T-E-M encourage teachers to adopt lecture-based classroom practices that not only restrict students' academic development and growth [20] but also make students lose interest in STEM subjects [21]. Moreover, the approach supports teachings which are decontextualized from the real world and fail to create opportunities for student to learn through doing, applying and solving problems in real-life situations [22]. This encourages students to maintain separated and parallel views of subject content [6]. In turn, the products of silo teaching-based approaches find it difficult to understand the integration between and among STEM subjects and the real world. This fragmented acquisition of knowledge, values and skills is not in sync with the competences demanded by twenty-first century economies. It is also not aligned to the STEM education form that endeavours to make students realize the integrated or holistic sense of their world living. Conclusively, this approach is limited in capacitating students with the dearly need twenty-first century competences.

The second STEM education path is the integration of two of the four STEM disciplines. This is described in this chapter as the duet STEM education approach. As an example, in schools this duet approach can concentrate on science and mathematics (SteM). Integrating science and mathematics (SteM) seems to be the preferred approach to STEM education in most schools among nations [17, 23]. This duet approach can be thought of as discipline based. The discipline-specific level of the STEAM pyramid [24] can be related to this STEM teaching way. In the pyramid framework, this level is described as where individual fields or disciplines are taught as stand-alone, but the focus becomes the base discipline where the teaching connects with other subjects. This is to say the subject of focus is covered in depth in relation to other STEM subjects. The specific area of academic expertise and related careers is more apparent and significant. This approach is considered more appropriate to secondary education [24]. The approach retains discipline identity and therefore befitting not only to educators but other professionals who have been trained in and associate themselves with specific disciplines like engineering. Within this approach, subject-based connections are done in a way that does not make a subject lose its uniqueness [25].

It is convincing from the definitions of each of the STEM disciplines that excluding one of them most likely creates competence gaps in student which will limit them in handling real-life problems. This is captured in this quote that 'We now live in a world where; you can't understand Science without Technology, which couches most of its research and development in Engineering, which you can't create without an understanding of Mathematics' [24, p. 17]. Thus, an understanding of what each STEM field is makes this assertion clearer. These fields are chronologically described [17]. First, Science (S) focusses of what exists in the natural world. Scientist engages in scientific inquiry, discovery and exploration to understand the world. In schools, colleges and universities, curriculum courses like biology, chemistry and astronomy aim to make student understand the specific aspects of what the world holds. Second, the Technology (T) is concerned with what can be designed, made and developed from materials and substances in natural world to satisfy human needs and wants. It alters the natural world through inventions, innovation and practical problem-solving as well as design processes. Third, Engineering (E) applies mathematical and scientific knowledge to develop ways of economically utilizing the materials and forces of nature in order to benefit mankind. It draws from technology to produce resources such as energy uses through creativity and logic [24]. Technology and engineering disciplines are strongly connected [17]. Finally, mathematics (M) is the science of patterns and relationships [numerically and symbolically expressed] and provides specific language for technology, science and engineering. Actually the practices of scientist, technologist and engineers are STEM integrated [6]. My talk with my children and siblings in architectural, electronic, automotive engineering all confirmed these authors' assertion that practitioners in these fields draw from various science disciplines, mathematics and technology in doing their work.

The third way is to integrate one of the STEM disciplines into the other three being taught [17]. For example, engineering content can be integrated into science, technology and mathematics courses. This author says this path may be depicted as E S-T-M. This is differentiated from integrating technology into the author by referring to this form as T S-E-M. This approach attempts to address the limitation of the duet way that focusses only on mathematics and science. However, it still conserves the discipline characteristics. One model suggests that STEM integration can be achieved through using engineering or technology designs to create connections of concepts and practices from mathematics or science [5, 26, 27].

Lastly, an infused model of the all four disciplines into each other to teach them as an integrated subject matter [17]. This way of STEM teaching relates to interdisciplinary meaning of STEM education [28]. The different expressions of this form of STEM education all converged to a blended approach that draws classroom practices (purpose, content, context, pedagogy, assessment and interactions) from all four fields and merges the into one field. For example, STEM integration as interdisciplinary involves cutting across subject interconnections into interdisciplinary content and skills [5], in that it mixes STEM content areas into a one subject learning area [29], an interdisciplinary teaching approach that removes the barriers among the four disciplines through incorporation of all the knowledge domains and individual subject skills into one [30]. This form of STEM education requires teachers to hold appropriate knowledge, skills and beliefs of each discipline so that students gain holistic competences for understanding and tackling world problems [31]. This integrated content mirrors the multidisciplinary nature of problems encountered in the real world. Integrated STEM education has promised to equip students with the long sought after skill to link the book with real-life problems and to provide hands-on approach which help motivate students to take up STEM subjects. Research indicates that using an interdisciplinary STEM education provides opportunities for relevant and more thought-provoking experiences for students [32]. Such experiences stimulate higher-level thinking skills and problem-solving. Ultimately, the effective implementation of this approach makes students better problem-solvers, innovators, inventors, self-reliant, logical thinkers and technologically literate [29].

Today, the interdisciplinary approach in STEM education is commonly accepted. It emphasizes on the matching of what it taught and learnt to the real world. Students are to make connections between school and the society [28]. The approach progresses nations towards STEM-literate societies which are compatible with twenty-first economies.

3.2 Integrated STEM education

The integrated STEM education entails 'an interconnected entity [of disciplines] with a strong collaborative connection to life' [31, p. 79]. This STEM education approach directs teachers to diffuse paradigmatic knowledge, skills, values and language differences and teach the integrated discipline as one cohesive entity. In doing so, teacher and student interactions should take the centre stage to enable them to collaboratively construct new knowledge, skills and beliefs at the intersection of more than one STEM subject area. Driving such interactions in the classrooms necessitates that teachers comprehend STEM content and acquire supportive pedagogical content knowledge specific to their subjects as well as working knowledge in another [31].

This integrated approach argues that the 'real-life' application of STEM is naturally integrated. A mathematically rigorous science education (MRSE) argument that disputes the epistemological (paradigmatic) view of mathematics and science as distinct to an extent that they are imposable to integrate illustrates how this model functions [31]. This argument aligns the insightful thinking that desperate epistemological assumptions underlying STEM disciplines detract their integration [33] and the interdependence relevance of science and mathematics to real life [34]. This interdependence of science and mathematics perspective afore their applications into real-world situations. Thus, the application of sciences and mathematics in engineering and technology invalidates their compartmentalized views and brings in an understanding of STEM education as an integrated entity.

STEM teaching can occur at the space where two or more STEM subjects such as mathematics and science intersect. Class interactions draw into this space the content and processes such as problem-solving and quantitative reasoning of both mathematics and science. Mathematics used in science or mathematically rigorous science education brings to the attentions of teachers an interdisciplinary understanding of STEM education that 'does not create an independent meta-discipline while preserving the subject-specific knowledge, skills, and attitudes' [31].

3.3 A continuum approach

The continuum approach borders on four different levels ranging from the lowest level 1 (the disconnected) to the highest level 4 (the integrated) [23]. The other possible ways of STEM integration it provides are the connected and complimentary in levels 2 and 3, respectively. In the disconnected level, individual STEM subjects are taught and learnt separately. These subjects such as chemistry, biology and mathematics exist parallel to one another in school curricula. Each subject is taught by teachers trained to teach it. STEM integration within this level entails introducing the subjects like engineering and technology in the school curricula which are usually excluded in schools. Like the separatist or silo approach of the pathed STEM education approach [17], this disconnected level guides the teaching and learning of specific STEM subjects. This level 1 STEM teaching and learning not only perpetuates the disparateness among multiple disciplines but also decontextualizes learning from real-world activities. It retains the status quo of teaching and learning of each STEM subject which has long been seen as lacking in instilling economic development driving skills such problem-solving, critical thinking, collaboration and creativity in students [35]. Yet, highly ranked infused (see Section 3.2) and integrated (see Section 3.3) STEM education approaches make it clear that this curriculum reform is not only about introducing engineering and technology in the school curricula as stand-alone subjects, but it is about integrating concepts from different subjects into new STEM subject matter, using student-centred pedagogies and assessment approaches in a way that nurtures students' 'inventiveness, creativity, and critical thinking'. Thus, the level 1 approach promotes traditional silo practices rather than integrative (innovative) practices.

Literature points to the thinking that introducing engineering and technology as stand-alone subjects will in some way bring awareness of their connections to the science and mathematics. This can be discerned from the definition of each of the four STEM disciplines. Science has three interrelated dimensions: (1) understanding nature which relates to science as the tool for understanding universal patterns of nature, (2) scientific inquiry which relates to the methodology used for generating knowledge and (3) scientific enterprise which relates to the human involvement in generating knowledge [23]. Mathematics is not only the primal language that cuts across STEM disciplines but also a network of practical and theoretical divisions that interact with other subjects as well as within [24]. It is inclusive of numbers and operations, algebra, geometry, measurement, data analysis and probability, problem-solving, reasoning and proof and communication (including trigonometry, calculus and theory) [23]. Both engineering and technology apply science and mathematics. Engineering uses technology to innovate and create products or structures and process that improves quality of life. Research is consistent that integrating engineering practices and engineering design on the learning of science potentially makes learning meaningful, exciting and relevant. Recent research, however, is focussing on pedagogical integration of engineering into other STEM subjects [27, 36].

The integrated approach, in level 4, informs integrative STEM classroom practices. This integrated approach is in synch with both the infusion model [17] and the integrated STEM education model [31]. Though different terminologies are used to describe this STEM education approach, they all converge on its description as an intertwined approach of the four STEM disciplines in a way that makes it impossible to distinguish each of them. Thus at classroom level, integrated STEM education informs development of integrated content (STEM content) [5], designing and adoption of student-centred pedagogies that support integrated learning [35] and adoption of assessment approaches that promote creativity, inventiveness and innovation in solving real problems. Such classroom practices should depart from the discipline-based student-centred pedagogies, real contexts and problem-solving STEM-integrated practices. The paradigm shift, therefore, calls for new pedagogical models, new content, assessment method, contexts and teacher-learner roles. Further, it necessitates higher education institutions (HEIs) to develop new STEM teacher programmes. The movement from level 1 straight to level 4 would be very abrupt, challenging and expensive. The levels 2 and 3 of this continuum approach can provide midway step progressions towards level 4.

The connected perspective in level 2 refers to drawing attention to connection between the areas while still considering them separately. Within this level teaching and learning is subject specific or discipline based. Though not explicitly stated, two options are available in this level. One is the duet approach of connecting the concepts of mathematics and science. This relates to subject matter or content connections. The second option is the one into three (1–3) STEM integration approach. This alludes to the E S-T-M integration of the pathed STEM education. STEM integration at this level is not to say that other subjects are excluded, but rather the focus is on exploring the primary subject more in depth and then the related fields. At this level, the specific divisions of silo are loosened and lessened through connections.

In level 3, complimentary approach informs teachers to explore mutual relationships between and among STEM subjects rather merely connecting concepts drawn from areas. The term complementary implies use of both differences and similarities of two or more things such as role or skills or strengths to create synergies that bring greater efficiency and effectiveness. Thus, the complementary STEM education notions that the four disciplines are different, but share similarities that can be drawn into a common space. In STEM education, STEM subjects may be offered separately, but the teaching of each specific subject should draw from other STEM subjects in order to develop knowledge and skills from combined strengths.

3.4 STEAM education

The STEAM linkages can be drawn from the articulation that 'We now live in a world where; you cannot understand Science without Technology, which couches most of its research and development in Engineering, which you cannot create without an understanding of the Arts and Mathematics' [24]. These ideas can also be drawn from the STEAM education framework for students with disabilities [7]. In simple terms, this approach entails an addition of the arts to STEM (STEM + arts). Considering students' frustration from unpleasant and/or unsuccessful experiences in STEM disciplines, some researchers suggested students' motivation in learning STEM disciplines needs to be additionally considered within the interdisciplinary framework [33]. They argued that STEM education should be expanded to embrace and integrate with the disciplines of the arts in order to facilitate and promote accessibility of STEM learning. The arts domain embeds areas of performing arts (i.e. dance, music and theater), presenting arts (i.e. visual arts) and producing arts (i.e. media arts), as well as languages. It is acknowledged that in real life, people solve problems through integrative thinking and applications. They do not separate aspects of science, mathematics, art, and so on [37], rather they draw from all the disciplines and confront the problem(s) holistically.

4. The STEME integration framework

The Science, Technology, Engineering and Mathematics Education (STEME) model in **Figure 1** was developed with full recognition that education is contextual,

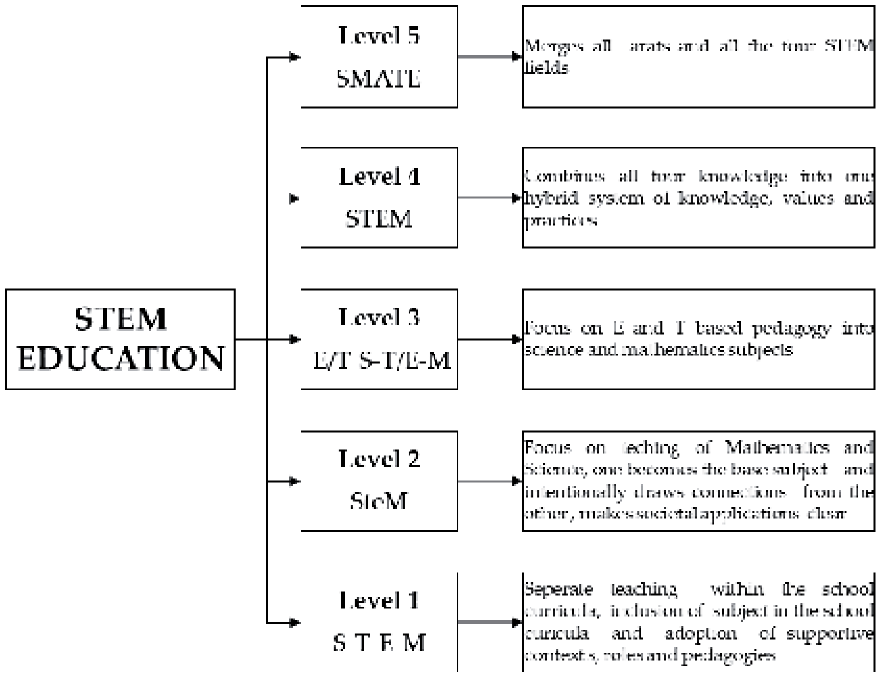

Figure 1.
STEME model.

so STEM education cannot be spared. My mission was to awaken nations into realizing the dire need for providing guidelines. The model was built through comparing and contrasting the four approaches to STEM education discussed in Section 3. Established connections among the four approaches were linked and ordered into a four-leveled STEME model. This framework elucidates on both paths and degree of integration.

Levelling of these approaches was based on their complexity and easiness to comprehend and implement. The lowest level 1 is the separatist approach, abbreviated S-T-E-M. The hyphens between the letters symbolize the side-by-side teachings of STEM subjects. Within this approach, integration is arrived by adding the STEM subject to the school curricula. Literature provides that this is one option for integrating technology into the school curricula [35]. In a simple understanding of STEM education as technology, engineering and mathematics, schools to include the missing discipline, usually technology and engineering to their curricula. This is a simple form of STEM education which is easy to implement [36]. All it requires is to train engineering and technology teachers. The traditional identity of the separatist approach brings not only its history and philosophy of subject specificity but also that of its separate disciplines. The current use of this approach can be inferred from policies that aim at increasing the number of STEM subjects or courses or academic programmes in educational institutions. Such policies also focus on addressing the dwindling enrolment problems and gender disparities in STEM fields. But STEM pedagogical integration can be effected in the teaching of specific STEM subjects. Many nations like Zimbabwe are advocating for shifts in pedagogical practices within the teachings of these disciplines. In Zimbabwe, 'new' STEM curriculum framework encourages teachers to adopt research, discovery and problem-based approaches in teaching specific STEM subjects. The adoption of these student-centred approaches in teaching subjects like chemistry should be able to develop creative and innovative minds in students. Classroom practices emanating from pedagogical STEM integration should be able to meet the criteria for an effective STEM instruction. Students in a pedagogic STEM integration classroom should be able to: (1) solve problems, (2) innovate, (3) invent, (4) logical think, (5) self-rely and (6) technological literacy [22]. Research has shown that by and large pedagogical STEM-integrated classrooms address problems related to subject conceptual understanding, poor achievements and loss of interest and enrolment declines. Other research findings teach us that teachers' subject based trainings and teaching experience support traditional teacher centred approaches and make the pedagogically limited implement STEM education. The need to professionally develop teachers for STEM teaching therefore needs no emphasis.

The STEME level 2–4 approaches allude to STEM integration that involves more than one subject. Generally, this integration approach is more difficult to both understand and implement as compared to the separatist [36]. The ordering of the three approaches was based on the logic that establishing connections between and among STEM subjects positively correlates with the number of the subjects involved. The more the subject to be integrated, the more complex it is to conceptualize and implement STEM education. The more the complex and cognitively demanding the subject involved in the integration, the more difficult the integration is to achieve. The duet integration in level 2 focusses on the teaching science and mathematics and making connections between them. The argument is that science leads to the understanding of nature that holds resource for sustaining life. So it would be difficult to effectively use such natural resources without understanding what the world has in store for humankind. The compartmentalization of science disciplines into chemistry, physics and biology aligns with the discrete approach to their study. 'Mathematics is not just a primal language for knowledge disciplines, but also a network of practical and theoretical divisions that interact both with other subjects' [24, p. 18]. This makes not only its linking it to any of the scientific disciplines practical, but also it can be used to mediate connections among science subjects. In fact, the 'real-life' application of sciences and mathematics in engineering and technology is practically integrated [31]. However, this level remains discipline based and directs teachers of chemistry, physics and biology to integrate mathematic in their teaching. Those of mathematics are also required to make connection to one or more scientific subjects. Like in level 1, the effective implementation of this approach requires teacher knowledge and knowledge of teaching in mathematics and a science subject.

The one into either three E/T S-E/T-M integration approach is in level 3. It describes the integration of either technology or engineering into one of the other three STEM disciplines. This approach suggests that engineering or technology reasoning, decision-making and practices can be integrated in science or mathematics or either engineering or technology classrooms depending on which subjects is being moved into the other. This type of integration is pedagogically based where engineering- or technology design-based pedagogy is adopted in science classrooms [30]. The US states, such as Texas, Oregon and Massachusetts, consented adding engineering to improve STEM education not as a stand-alone subject but rather pedagogically [5]. This curriculum movement lends the support of many researches that have shown that use of engineering designs in science classrooms effectively develops in students the much-desired twenty-first century skills [26, 37]. The same goes for integrating technology.

The STEM education level 4 depicts interdisciplinary or multidisciplinary integration. Though some studies attempt to distinguish these two constructs [9, 24], in this model they are collated to mean the same. The phrase interdisciplinary is used to entail an approach where STEM teaching integrates all the four disciplines into one cohesive teaching and learning paradigm [28]. I use the term parading from its description as a set of interrelated beliefs about reality, knowledge, methodology, values and language

(Mpofu et al. 2016) in relation to STEM teaching. The main aim of interdisciplinary integration is to shift traditional paradigmatic barriers existing among the four disciplines to STEM [38]. Within this interdisciplinary approach, teachers are expected to guide students to make connections between school, community, work and the global enterprise through coupling the learning academic science, technology, engineering and mathematics concepts with real-world lessons [28, 26]. Moreover, interdisciplinary learning impacts lifelong learning habits, academic skills, personal growth [39] and development of knowledge management skills [40].

The last level 5 approach described in this model as Mathematics, Science, Art, Technology and Engineering (MSATE) has been modified from the STEAM approach. STEAM education for students with disabilities can also be adapted to all students. In simple terms, STEAM education means an addition of the Arts to STEM (STEM + Arts). In a level 5 approach in SEME, it is abridged MSATE to depict its integration of all knowledge bodies into one holistic knowledge, values, skills and practice system. This letter arrangement taps arguments proffered by indigenous scholars that science is cultural and language is central to every culture and development of its knowledge. The art domain in this context embraces both languages and social sciences. It is positioned in the centre to depict that inherent in it are knowledge development, representation and communication. Mathematics and Science come before Arts to reflect the connecting role Mathematics plays across STEAM disciplines and the understanding of nature fundamental role Science plays. Thus, the language understanding of both sciences and mathematics enables their combined applications in technology and engineering. Thus, MSATE takes cognisance that language use is integral to activities (e.g. classroom teaching) that are placed within social contexts [37].

5. Practicalizing the STEME theoretical framework

This section presents one way a nation can apply this framework. The framework should be used on an understanding that the actual implementation of STEM education is a mammoth task and process. Therefore, its implementation is a responsibility for all: academics, policymakers, schools and industries as well as communities.

The first step is to build a collaboration team composed of critical STEM education stakeholders. Among the team members should be renown scholars in STEM education drawn from the nation's universities, Ministry of officers in research and technology departments, policy makers, teachers of different STEM subjects, parent or guardians representatives, student representatives industrialist. This team should be selected based on competence, relevant experience and context as well as passion. Time should be taken to capacitate the team through workshops, seminars, symposiums and exchange programmes.

The collaborating team in the second step involves a critical and holistic analysis (CHA) of the status of STEM education in their nation through various researches that use the STEME theoretical framework. This CHA should include the nation's STEM education rationale, goals, intended outcomes, components and how the components interact as well as the implementation challenges. In the STEME framework in **Figure 1**, this activity pertains to the cell—/box-labelled STEM education. The CHA findings should lead to the conclusion that describes the national status of STEM education within or between levels of STEME. This is shown by the direction of arrows. For example, from CHA it can be concluded that our STEM education is largely at level 1. Implications of the finding in relation to the rationale, goals and intended outcomes and impacts are then discussed.

In the third step, the STEM education team identifies their nations' desirable STEME level. I recommend three ways to identify this level. One is to draw it from the goals and intended outcomes and impacts established in step 2 above. For example, on one hand national agenda that seeks to develop and grow its economy through capacitating a critical mass of skilled manpower in STEM-related careers might be aiming at operating at level 3. On the other hand, a nation that seeks to develop and grow its economy through industrialization and entrepreneurship might be at achieving either STEM level 4 or 5. The other one is to consider the best-fitting level to the needs of the nation based on the comparative analysis of the disadvantages and limitations of each level of operation. Finally, a blended approach of two ways can also be adopted.

The fourth step is assessing national needs and constraints in relation to the status and desired STEM level gap. Let's say the status and desired levels were established as 1 and 3, respectively. The team identifies the needs and constraints to move from the status level to the desired level. In step 5, the STEM team develops a STEM implementation plan to take the nation to the desired level including strategies to address the identified obstacles for effective STEM teaching at that level. The last step is to implement the plan.

6. Conclusions and recommendations

This chapter responded to the globally growing calls for an urgent need to put in place clear national frameworks to inform in developing and implementing STEM education at classroom level. There are four main conclusions drawn from the discussion in this chapter. First, the starting point to realize the endeavours of STEM education is for nations to clearly define their theoretical framework. The chapter suggests a STEME (Science, Technology, Engineering and Mathematics Education) integration framework as a starting point for better understanding and operationalizing STEM education. It orders a variety of STEM integration approaches from level lowest level to highest level 5. Second, collaborative engagements of experts are to be used in a six stepwise implementation of STEM education process. These are building a national STEM education collaborating team, critical and holistic analysis of the status of STEM education, identification of the desirable level of STEME level, assessment of the STEM education needs, developing an implementation plan and implementing the plan. Third, the idea of driving STEM education from a well-defined national theoretical framework like STEME can be an effective mechanism for facilitating innovative STEM education practices at classroom level. Lastly, the strength of theoretical framework such as STEME is in systematically contextualizing STEM education from a research and well-defined context. This is of critical importance in light of the significant variation across individuals, nations and disciplines with respect to current understandings of STEM education and its core components. The framework underscores that implementing STEM education requires correct interpretations and deep understandings of its endeavours from national level that cascades down to classroom level. The paper recommends that the developments of national STEM education approaches inform not only STEM teaching but also the development of teaching materials such as textbooks. The strength of this STEME theoretical framework is not only in its adaptability to different contexts but also in its easy to operationalize. The chapter further recommends researchers to use STEME as a springboard for further communication and research exploring the successful implementation of STEM education in their nations and beyond.

Final thoughts

While the success of STEM education relies on many factors, the most important factor of this reform is teachers' classroom practices that foster the development and use of the twenty-first century competences. This hinges on the quality of the teachers and their understanding, marriage to and competencies in STEM education. The teachers will require a lot of support in terms of guiding frameworks, professional development, material development and many other resources. The theoretical framework such as STEME is the key that guides training and retraining, research and monitoring and evaluation of STEM teaching. But above all, the STEME theoretical framework brings about a shared meaning and spirit of STEM education among stakeholders. This chapter motivates me to initiate the practilization of STEM education in Zimbabwe.

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Section 3

Theorising Mathematics Education

Chapter 9

Formative Assessment in Mathematics Education in the Twenty-First Century

Benard Chigonga

Abstract

Assessment does not always have to involve paper and pencil but can instead be a project, an observation, or a task that shows a student has acquired the concept and can make sound connections and linkages with other related concepts. Learning is meaningful when the student comprehends the relationship of what is being learned to other knowledge. Furthermore, concept map measures aspects of learning, which conventional tests cannot measure such as students' misconceptions. As such, the chapter shall focus on formative assessment in mathematics classroom mediated by a method of teaching (concept mapping) that promotes critical thinking, which assists teachers to teach and assess students' understanding and make connections between concepts explicitly.

Keywords: assessment, formative assessment, summative assessment, concept mapping, instructional tool

1. Introduction

In mathematics education, focus is on the interactions among the three components of an instructional unit, the teacher, material, and students. In other words, the capacity to deliver quality instruction depends not only on the individual teacher's intellectual and personal resources but also on his or her interaction with specific groups of students and materials. According to [1], all curricula exist to provide the basis for effective instruction, that is, instruction that maximizes learning. Effective instruction is a result of proper and extensive planning. Planning starts with organizing material from the mathematics content. After deciding what material will be used, the next step is sequencing that material in the way students will experience it [1]. If instruction requires all three components (the teacher, students, and materials), then the capacity to produce worthwhile learning must also be a function of the interactions among these three components. Students bring experience, prior knowledge, and habit of mind, and these influence how they apprehend, interpret, and respond to materials and teachers. Teacher's awareness of students' "capabilities, needs, and past experiences" and the ability to use this information to "create a learning situation in which students can meet their needs or solve a problem in an autonomous and independent way" is therefore important.

Assessment is the process of gathering information so as to monitor students' prior knowledge and progress and make sound instructional decisions.

As such, the primary purpose of assessment is to improve student learning of mathematics. Teachers examine the standards, assess where their students are in their knowledge base through some sort of pretest, and then plan their instruction based on the data collected (diagnostic assessment). During the process of teaching and learning in the classroom, teachers do assessment for learning (formative assessment) and assessment of learning (summative assessment). They then compare assessment for learning and assessment of learning in order to determine whether or not the implemented learning activity in class should be used again (or modified) [20]. A test score as feedback that measures whether a student has attained the expected standard cannot serve as formative assessment. Teachers need students' background information in order to modify teaching and learning activities to improve their learning. Therefore, feedback that involves a focus on the detailed content of what is being learnt has a central function of formative assessment [4]. Formative assessment or assessment for learning involves a continuous way of checks and balances in the teaching and learning process. It can be done at the beginning of instruction to tap prior knowledge in order to connect concepts when motivating for upcoming new concepts. The method allows teachers to check their students' progress and shortcomings as well as the effectiveness of their own practice, thus allowing for self-assessment.

The functional role of formative assessment (assessment for teaching) is often compromised in light of growing demand for external accountability related to performance and learning outcomes. Accountability pressures put many (mathematics) teachers between striking a balance between teaching mathematics facts and calculation procedures and also developing a conceptual understanding of mathematics. Due to accountability pressures, teachers have a tendency to focus on the preparation for examinations, where they opt to provide students with the necessary skills by working out problems similar to those that have occurred in past examination papers. This approach has dismally failed because student performance in mathematics remains depressed. Mindful of that, it is deplorable that the state of affairs concerning the functional role of formative assessment (assessment for teaching) is often overlooked. During the process of teaching and learning, teachers should assess the impact of their teaching on their students with the intention to create optimal learning spaces that meet the learning needs of each student. Therefore, teachers are discouraged from thinking of assessment as pencil and paper and embrace alternative forms of assessment in the teaching and learning of mathematics [2]. They should try to check on the performance of each student by giving class daily written exercises and mark the exercise books before the next day lesson. Also they should and always carry out weekly informal tests. Carrying out formative assessments in the form of informal tests, written classwork, or homework provides continual snapshots of students' progress throughout the week, month, or school year. By using these formative assessments, teachers can target students' specific problem areas derived from qualitative feedback (rather than scores), adapt instruction, and intervene earlier rather than later. The qualitative feedback about students and their abilities are likely to improve teachers' mathematics knowledge in teaching (which is demonstrated in the class by how well a teacher uses mathematical and pedagogical knowledge to help students learn mathematics) [5]. As teachers are guided by the qualitative feedback from the formative assessment, the critical component that must be present in any intervention is an opportunity for the students to discover the joy of creating knowledge from their own experience of the subject matter. Hence the activities that the teacher creates should be student-centered. Besides, when teachers' classroom assessments become an integral part of the instructional process and a central ingredient in efforts to help students learn, the benefits of assessment for both teachers and students will be boundless [5].

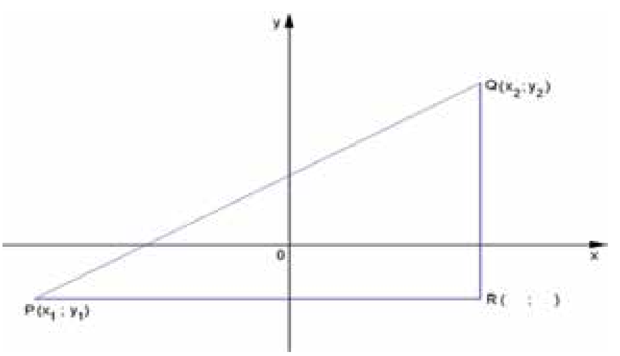
2. Formative assessment in mathematics classroom thrives on teaching approaches that promote critical thinking

In the process of teaching and learning, there are myriad factors that impact on student learning. However, how well a teacher uses mathematical and pedagogical knowledge to help students learn mathematics is one of the factors that influence student success. As such, teachers should strive to expose students to teaching practices that stimulate critical thinking process whose salient features are conceptualizing, applying, analyzing, synthesizing, and evaluating information [3]. It is therefore important for teachers to provide enquiry or problem-solving approaches in mathematics classes. Infusing critical thinking skills into didactic activities requires teachers to consciously integrate new knowledge with already existing knowledge schema of mathematics content [3]. Students battle to recall and apply basic concepts of mathematics in the resolution of mathematical problems, and this leads to the lack of understanding of mathematics [18]. Concept mapping can be used by teachers to stimulate critical thinking in students because it represents and organizes knowledge, helps retention and recall of concepts learnt, and provides feedback on the understanding of the concepts learnt [4]. Therefore, thinking of assessment as a task that shows a student has acquired the concept and can link with other related concepts becomes paramount [3]. Accordingly, learning is meaningful when the student comprehends the relationship of what is being learned to other knowledge. As such, there is a need for teachers to incorporate the concept mapping in the formative assessment process as this will help them diagnose students' misconceptions [4]. If students can link new information to their existing conceptual framework, they can construct new, meaningful interconnections, so that their existing conceptions are transformed, enriched, or revised, and conceptual change occurs. This is achieved by carrying out formative assessment where students are asked to summarize at the end of instruction to allow them to make connections [1]. Therefore, existing conceptions are transformed during construction of understanding [5]. Interaction, collaboration, cooperation, dialog, and discourse are key concepts facilitated by formative assessment for the effectiveness of instructional activities. As such, collaborative group learning fosters meaningful learning and new knowledge construction [4].

3. Assessment for learning versus assessment of learning in mathematics

Assessment is generally broken down into three categories: assessment before instruction (pre-assessment), assessment during instruction (formative assessment), and assessment after instruction (summative assessment). It could be argued that pre-assessment is both assessments of and for (as) learning—that is, it assesses "prior knowledge" (as a pre-assessment) and that data is then used to revise planned instruction (making it formative assessment). Assessment of learning is used to determine what students have learned, while assessment for learning is used to determine what students are learning. It should be clear that assessment for (as) learning is a process of gathering information about students learning and provide qualitative feedback to support individual student learning and improve teaching practice in the classroom. However, there is a significant overlap between assessment of and for learning. Therefore, learning for assessment (summative assessment) and learning from assessment (formative assessment) are two complementary purposes of assessment. For example, the same test given in one circumstance would be considered an assessment of learning, while in another circumstance be considered an assessment for (as) learning. In short then, the difference between assessment of learning and assessment for learning is a matter of function and purpose [17]. Hence assessment that occurs during the lesson to continuously assess learning throughout instruction is formative assessment. For example, in teaching mathematics, I often use concept learning where students are given an explanation, examples, and non-examples after which they engage in working problems on their own or in groups. Periodically during the lesson, I stop students and have them share their answers. This allows me to know if everyone is on the task, if everyone has understood, and whether I have to revisit the instruction in a different way if students are making several errors. At the end of instruction, assess whether or not the instruction was effective and whether the students have gained the knowledge as per lesson objective, and if they have not, then the instruction is redesigned to better cater for the students. Therefore, "if the students do not learn the way we teach them, we must teach them the way they learn [1]." I shall not give an example of *assessment of learning* task because it is predominant in high schools. However, hereunder is an example of *assessment of learning task* anchored on discovery-based learning. The objective of the task is to help students derive and apply the distance formula for calculating the length of a line segment joining any two given points.

1. Given the diagram below:



   a. Determine the coordinates of R.

   b. What is the horizontal distance PR?

   c. What is the vertical distance RQ?

   d. What type of triangle is PQR?

   e. Find the length of PQ.

2. Use the answer you found in 1(e) to calculate the length of the line segment joining points $A(3;4)$ and $B(-2;7)$.

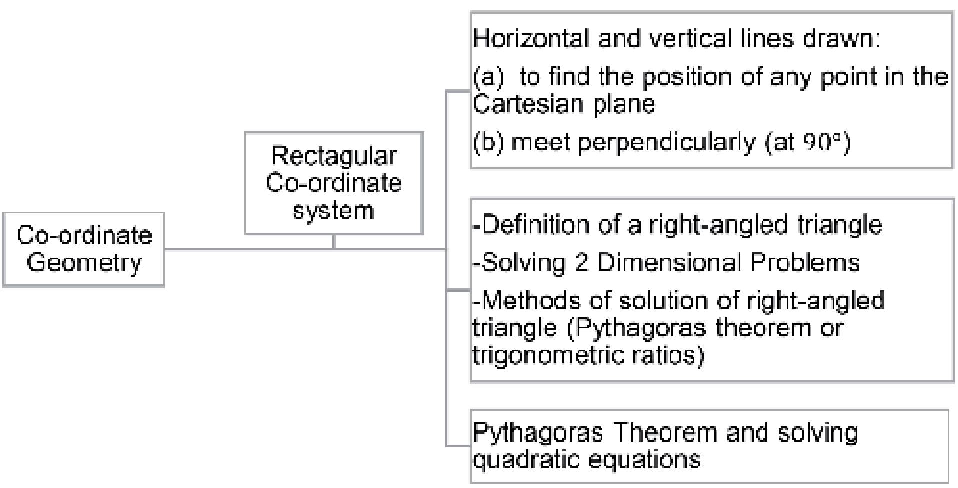
3. Generate a concept map in relation to concepts used to find the distance formula.

Solution strategy:

Question	Answer	Concepts employed to arrive at the answer
a)	$(x_2;y_1)$	*Rectangular coordinates
b)	$x_2 - x_1$	* Distance moved from point P to point R (horizontal displacement)
c)	$y_2 - y_1$	* Distance moved from point R to point Q (vertical displacement)
d)	Right-angled triangle	* Horizontal and vertical lines meet perpendicularly (at 90°); hence $PR \perp RQ$
e)	$PQ^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2$	* Pythagoras theorem (result is a quadratic equation)
	$PQ = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$	* Solution of quadratic equation (consider the positive solution because we are dealing with distance)
2.	$AB = \sqrt{(-2-3)^2 + (7-4)^2}$ $= \sqrt{(-5)^2 + 3^2}$ $= \sqrt{25+9}$ $= \sqrt{34}$	*Application of the distance formula *Leaving answer in surd form

In Question 3, students will be assessed on how they organized their knowledge when finding the distance formula. Also it allows the teacher to establish how students understand concepts related to Cartesian coordinate system such as rectangular coordinate system, and methods of solving a right-angled triangle and algebraic processes such as solving quadratic equations. Thus the number of links of concepts tells the teacher the knowledge gaps inherent in students' connections between and among mathematical ideas, thereby using concept map as a teaching and learning strategy [5].

The concept map below provides a summary of the different concept employed in the process of finding the distance formula:



4. What are the assessment tools in mathematics?

In the process of teaching and learning, teachers facilitate, observe, and assess student learning. This can be achieved by making learning practical through meaningful activities, embracing collaborative learning, using quizzes to engage students in reflections, or asking students to summarize lesson taught. The assessment tools they may choose to apply to assess student learning may differ depending on the stage of learning. However, assessment only *of* learning (summative assessment) and not *for* learning (formative assessment) is not enough to promote students' integrated understanding. They may use concept maps (connections between and among mathematical ideas), concept tests, examinations, oral and poster presentations (use different representations of mathematical ideas to support and deepen mathematical understanding), peer and self-assessment (introduce the peer or self-marking of home/classwork in the classroom, and allow for discussion if there is a disagreement of an answer), portfolios, rubrics, or written reports. All these forms of assessment tools in mathematics allow for ways of assessment that motivate students to learn and thereby avoid damage to student self-esteem [7]. Besides, these different forms of assessment tools give helpful feedback to students in that they are guided on how to avoid making similar mistakes in the main examination. Furthermore, students are guided on how to improve their performance, and this impacts positively on student learning [7].

5. What makes a good mathematics classroom assessment?

A good classroom assessment plan gathers evidence of student learning that informs teachers' instructional decisions. It provides teachers with information about what students know and can do. Students should, at all times, have access to the assessment, so they can use it to inform and guide their learning. However, how can assessment be used to improve mathematics teaching?

Using classroom assessment to improve both teaching and student learning is not a new concept. But assessments designed for evaluating student performance through scrutiny of examination results (test scores) will not help improve instructional practices of teachers that enhance students' learning. Assessment for learning should be treated as an integral part of an instructional process and as an essential element in teachers' effort to help students learn. It is encouraged that before teaching students, teachers should employ baseline assessment to see what students already know. During the learning experience, teachers should employ formative assessment to address the misconceptions that may arise and after the learning experience; summative assessment should be employed for evaluating the effect of the instructional process on student knowledge. There is then a need for balanced packages of assessment tools, with all the elements of fair testing in it. A teacher can use concept maps, concept tests, examinations, oral and poster presentations, peer and self-assessment, portfolios, rubrics or written reports investigations, projects, class activity, and weekly or fortnightly concept tests as forms of assessment instead of using only tests as forms of assessments. However, to use classroom assessment to make improvements, a teacher should employ all forms of assessments, i.e., baseline, formative, diagnostic, and summative assessments. The choice of methods of scoring students in these different forms of assessments is guided by the purpose of assessment. Methods of scoring students should be such that they enable the student to demonstrate what they know rather than what they do not know. A teacher may elect to use a rubric because it enables him/her to score students on all their thinking processes and not only focus on one correct answer [6]. In that way teachers would be able to identify the misconceptions that students have and employ appropriate teaching strategies when addressing the misconceptions. Very often testing is meant to find out what the students do not know. This is a rather negative approach, and it does not give the students a chance to show what they do know [6]. One result may be that the student loses confidence. Assessment should support learning; it should not be a judgment. Therefore the techniques a teacher may use in a mathematics classroom to make students understand better help them become more independent and stimulate their critical thinking [8]. Therefore, what stands out to be a good mathematics classroom assessment for teachers is to change their instructional approaches (techniques) in three ways:

- Use *assessments* to establish and describe the students' misconceptions.
- Turn these misconceptions into teaching and learning opportunities.
- *Give students second chances* to demonstrate success.

5.1 Use assessments to establish and describe the students' misconceptions

Teachers' knowledge of students' misconceptions should go a long way in equipping them to prepare mathematics activities in their classroom. This will allow them to plan instruction targeting the student misunderstandings. I can conclude that formative assessment, like homework, can be used to locate mistakes and to figure out why they were made and how to provide support to students by way of explanation and tutoring [19]. This approach can help teachers learn some pedagogical lessons from exploring the content of students' procedural knowledge and understanding [9]. That is, when students make mistakes, they must be considered as opportunities for reconstruction of their knowledge.

5.2 Turn these misconceptions into teaching and learning opportunities

Assessment must be followed by corrective instruction designed to help students remedy whatever learning errors are identified with the assessment [10]. Using corrective instruction is *not* the same as reteaching, which often consists simply of restating the original explanations louder and more slowly [12]. Instead, the teacher must use strategies that accommodate differences in learning styles and intelligences [13]; for example, to teach circle geometry, I gave the students all the different circle theorems and then showed them several circle questions to identify the theorems within and find missing angles using these theorems. There was no success in this type of instruction as students did not remember the theorems; hence, they could not identify or apply them in questions. I decided to alter instruction by creating different circle handouts where students were directed to draw lines to create the theorems, measure the angles with groups, and infer circle theorems based on what they observed. This new instruction of circle geometry gave far better results as students were remembering most of the theorem since they discovered them on their own. However, students who had few or no learning errors to correct also participated in the enrichment or extension activities and that helped them to broaden and expand their learning.

5.3 Give students second chances to demonstrate success

Teachers should strive to help their students become lifelong students and to develop learning-to-learn skills [10]. What better learning-to-learn skill is there than learning from one's mistakes? Mistakes should not mark the end of learning; rather, they can be the beginning. As such, assessments must be part of an ongoing effort to help students learn. If teachers follow assessments with corrective instruction, then students should be provided a second chance to demonstrate their new level of competence and understanding [11]. This second chance determines the effectiveness of the corrective intervention while giving students another opportunity to experience success in learning, thus providing additional motivation [11].

6. Conclusion

Is the assessment for the student or the teacher? If you are not clear about why you are assessing (and what you are going to do with the data the assessment provides) you are wasting a lot of time, energy, and resources—your own and that of the students [14]. Always attention should be given to the broader meanings present in the data such that, if need be, student debriefing should be done to shed more light on the thinking behind their identified misconceptions. Therefore, I hold the view that teachers have to have a plan of what they are going to do with what they learn from the assessment (the data) before they give the assessment—ideally, before one even designs the assessment to begin with. An important implication of this view is that there is a need for teachers to understand the importance of prior knowledge to learning in order to facilitate learning. Students build on what they already know and have come to understand through formal and informal experiences. As such, students' knowledge structure (or connected understanding) should be reinforced in all learning incidents. Therefore, it is important to identify the processes and associated domain knowledge that students activate and bring to the solution context [16]. To continuously connect concepts in the learning of mathematics, teachers then need to incorporate concept mapping in the formative assessment process. The use of concept map helps students identify their concept knowledge gaps in a nonjudgmental setting and then develop practical means for attaining that knowledge [15]. Also the use of concept map helps students to improve their skills in negotiating meaning and challenging each other's explanations. On the other hand, concept map (as a formative assessment tool) provides teachers with a snapshot of students' concept knowledge gaps during the teaching and learning process. The spin-off from incorporating concept mapping in the formative assessment process is informative and reflective feedbacks tailored to students' personal abilities. This information helps teachers to plan instructional experiences aligned to students' traits.

Unless mathematics teachers provide a learning environment that promotes understanding through interaction, students might only commit unassimilated information to their short-term memory through rote learning, and no meaningful learning will occur. Therefore, the use of extensive formative assessment, vis-à-vis concept mapping, to drive instruction and implement a variety of strategies for the purpose of differentiating the instruction is of paramount importance.

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Chapter 10

Towards a Forward-Thinking College Calculus Program

Jessica Hagman

Abstract

Calculus is perceived as serving many roles in college STEM students' education, including as a way to 'weed out' students who should not be in the major to teaching fundamental concepts. No matter its purpose, it is clear that college calculus is viewed as a critical course in university STEM education. It is also clear that in the US and other countries, STEM education is disproportionately serving men and white and Asian students. In this chapter, I discuss how calculus has come to occupy this position over time and the current state of college calculus drawing on two national studies in the United States. I then define a forward thinking-calculus program as one designed to support a diverse population of students to thrive, provide an example of a program aligned with this approach, and discuss key features to consider in designing a calculus program for the modern age.

Keywords: college, calculus, change, equity, STEM education

1. Introduction

In their summary of calculus education research, Rasmussen, Marrongelle, and Borba describe calculus serving the role of "everything from a 'weeding out' course to fundamental preparation to take on applied problems in partner disciplines, preparing students to bring an understanding of rates, concavity, functional relationships, among other topics to bring to bear on multi-disciplinary problems" ([1], p. 507). Calculus is often thought of as the college mathematics course, with the main goal of mathematically preparing students for degrees in STEM, but it is also often seen as beneficial to students in non-STEM degree programs for developing critical thinking and problem solving experience. As a researcher who has spent countless hours sitting in calculus classes across the country, at schools we have identified as having successful or interesting programs, I frequently find these classes stale, uninspiring, and certainly not supporting critical thinking or creative problem solving. As a mathematician who was inspired to study math because of calculus, I find this troubling, but as an educator I find it immoral. In this chapter, I will explore how calculus has come to occupy its current status as the gateway mathematics class for STEM students, discuss the current state of calculus drawing on my research teams' studies of college calculus for the past decade, and offer an example of a forward-thinking calculus program.

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2. How calculus established itself in STEM education

2.1 Brief history of calculus

The invention of calculus is traditionally given shared credit to Isaac Newton and Gottfried Wilhelm Leibniz, who each independently developed the theories around infinitesimal calculus in the late seventeenth century. Bressoud points out that their contributions to calculus lie in connecting theories related to differentiation and integration, rather than in developing the theories of the individual ideas [2]. Newton, primarily a physicist, was motivated to pursue calculus in order to provide a scientific description of motion and magnitude. When documenting his ideas related to calculus, he did so primarily for himself, using a mixture of notations that made sense to him. Leibniz, described as a polymath or someone with a wide array of knowledge akin to a renaissance man (specifically, his interests included metaphysics, law, economics, politics, logic, and mathematics), was motivated to pursue calculus in order to provide a metaphysical explanation of change. He purposefully developed a clear and consistent notation system to document his work that we still essentially use today. While these two men came to be interested in calculus for very different reasons (one from more applied motivations and one coming from more pure mathematical interests), today they continue to share the honor of being credited with this field.

Although Newton and Leibniz are credited with the invention (or discovery, depending on your scientific philosophy), many mathematicians came before them, to develop the ideas they built on, and after them to refine their ideas [3]. Even as recently as 2014, researchers are challenging the credit given to Newton and Leibniz by finding evidence that other mathematicians developed the formal ideas of calculus long before the 1670's. For example, a group of mathematicians in Southern India from the Kerala School developed and published work on many fundamental ideas of infinitesimal calculus 300 years prior to Leibniz and Newton [4]. With this note aside, college calculus today is a direct descendent of the work of Newton and Leibniz, using Leibniz's notation, and so I consider these as the birthplace of the college calculus we still see today.

2.2 Evolution of calculus education

So how did calculus come to hold the place as the integral (pun intended) component of so many students' college educations? To answer this question, I draw significantly from Alan Tucker's "History of the undergraduate program in mathematics in the United States" [5]. In the 1700s and 1800s, mathematics was studied as one of the main topics (along with Latin, Greek, and Hebrew) in college following the English college model. The goal of mathematics in such an education was as a "classical training of the mind instead of the language of science and engineering it is today" ([5], p. 689). The students attending these colleges were mostly male and mostly from the upper-class. Although Newton's and Leibniz's work developing calculus into a more systematized and valued field occurred in the late 1600s, calculus wasn't taught widely in college until the late 1800s. It was during this time period that colleges shifted from delivering a classical curriculum to a more practical curriculum. This is largely due to the fact that land-grant public universities were established in 1862 by the Morrill Act, and calculus became more standard for technically-oriented students.

By the early 1900s, most colleges allowed students to choose the courses for their study, which led to an increase in college enrollment and a decrease in mathematics study. It was during this time that mathematics was no longer viewed as part of a classic education, and instead a tool useful for engineers and scientists (as it continues to be seen today). During this time, calculus became an elective in US college preparatory high-schools and a mandatory subject for college preparatory high schools in Europe.

Also around this time, the presentation of calculus changed from following the order of topics in which the theory was developed (first integration, then differentiation, then series, and lastly limits), to the order most beneficial for rigorously proving theorems of calculus (first limits, then differentiation, then limits, and lastly series) [3]. Little has changed since this time. The undergraduate mathematics curriculum for mathematics majors has become more and more solidified, aided by guidance from the Mathematical Association of America and their Committee on the Undergraduate Program in Mathematics (CUPM) guide. Tucker notes that in the more recent history, though the curriculum has not changed much, "the greatest area of change and concern in the past 40 years has been the articulation between high school and college mathematics." By the early 1980s, "mathematics faculty were dealing with large numbers of students in freshman courses who showed limited knowledge of needed algebra skills" ([5], p. 702). He attributes these changes to states increasing their high school mathematics requirements and watering down the material to meet these higher expectations, as well as the rise of high stakes testing. Near this time, AP Calculus became an increasingly expected course in high school. During the late 1990s (during which time I was in high school and also the earliest data recorded online of AP participation by subject), approximately 100,000 high school students took the AP Calculus AB exam [6]. From my experience, AP Calculus AB was viewed as a course that only students extremely interested in pursuing mathematics or physics as their college major would take. By 2018 that number had tripled [7]. As part of a large, national study on college calculus conducted in 2010, my research team identified that two-thirds of all students in a college calculus class had already taken a course in high school called calculus (many of these being AP Calculus AB or BC), and half of the students we surveyed believed they needed to take a calculus course in high school to be successful in college [8].

Over the past nearly 50 years, there has been tremendous attention paid to reforming college calculus, which has resulted in more attention to problem solving in applied contexts, an increased focus on supporting students' development of conceptual understanding rather than only procedural fluency, and often more active learning techniques employed in the classroom, including student-centered instruction and more technology use [1, 9, 10]. These changes have certainly resulted in more variation in the college calculus instruction across the country, with some programs very much still rooted in these reforms and others holding on to a pre-reform calculus model. That said, the basic content being taught in all of these programs is still essentially a course on Newton & Leibniz's ideas, taught in the order best suited for proving calculus, regardless of the presentation, the students being taught, the pedagogy, or the contexts for the word problems.

2.3 Current state of college calculus education

For the past decade, I have been a part of a large research team studying college calculus. This research team has been led by David Bressoud, run under the auspices of the Mathematical Association of America, and funded by the National Science Foundation. Our research has come from two projects, the first begun in 2009 and focused on mainstream college differential calculus programs (typically called Calculus I) in all institution types, called *Characteristics of College Calculus (CSPCC);* the second begun in 2014 and focused on precalculus, differential and integral calculus programs at Masters and PhD-granting institutions, called *Progress through Calculus (PtC).* Our work has been generally focused on identifying aspects of college calculus programs that are more successful or innovative than comparative institutions, and supporting more mathematics departments to improve their programs based on these findings. For our purposes, success in college calculus is primarily marked by a large percentage of the students who plan to complete both differential and integral calculus (typically called Calculus I and Calculus II; requirements of most STEM-degrees) reporting that their confidence, interest, and enjoyment of mathematics did not decrease after the first course in calculus, and that these students primarily planned to continue studying calculus (and thus continue studying STEM) after taking the first course[1].

Overall, based on these measures, we did not see great evidence of success in college calculus across the country. Among the students surveyed, we saw significant decreases in confidence, enjoyment, and interest in continuing to study mathematics [8], and we found that nearly 18% switched out of the calculus sequence after taking differential calculus [12]. The main reasons for switching out of the calculus sequence given by students were changing their majors and no longer needing to finish the sequence, not having the time and effort to put into calculus to do well, and having a negative experience in differential calculus. Women students switched out at significantly higher rates than men, and disproportionately credited a lack of confidence in their mathematical abilities as the reason why [12].

From the 213 schools that participated in the CSPCC survey, we identified 18 schools that showed promise, including community colleges, Bachelor's-granting, Master's-granting, and PhD-granting schools. We conducted case studies at these sites, and based off of these case-studies have identified a number of components of calculus programs potentially related to student success. A collection of these findings can be found on our project website, www.maa.org/cspcc. For this paper, I focus on the findings that have had the most direct impact on the follow up study, PtC. From the five doctoral-granting departments we visited, we identified seven features that were common and that we believed were related to their success [13]. These features are: a coordinated calculus program, collection and use of local data to inform changes to the calculus program, rich and engaging curriculum, support of active learning, teaching preparation of the graduate students involved in the program, tutoring centers and other supports available for students, and adaptive placement systems into the calculus program. Since publishing those findings, we have seen a number of calculus programs across the country use these findings to guide improvements to their own programs, showing the impact that such studies can have on shifting the national landscape of calculus education.

I am confident these features provide concrete aspects of calculus programs that departments can focus their improvement efforts on, and that these are likely to lead to some improvements. However, I have recently argued [14] that it is also likely that focusing on these aspects alone can lead to programs making improvements that better serve the populations of students already being supported through calculus programs. In **Table 1**, I provide demographic data of the students earning Bachelor's degrees in any major, and specifically in STEM, from each school near the time of our data collection in 2010 from the five universities visited.

Table 1 highlights the low population of students of color at the institutions visited, and the lack of STEM degrees earned by women of all ethno racial backgrounds and students of color of both sexes. The percentage of students who switched out of the calculus sequence at these institutions varied drastically by institution, from as low as 2% at one technical institutions to 30% at one large, public. However, the trends of women students switching at higher percentages than men and low enrollment by students of color are common across each of these sites. A deficit-oriented interpretation of this data would argue that these differences in interest, success, and persistence by different student populations are due to internal deficiencies of some populations of students, playing into common

[1] The surveys used can be found at [11].

	PTI[2]	LPU1	LPU2	PTU	LPrU
Total	620 (542)	6473 (1822)	5323 (2004)	1073 (816)	6864 (1350)
Woman	26.1 (23.7)	51.2 (29.9)	52.5 (43)	21.7 (15.2)	50.9 (23.7)
White, non-Hispanic/Latinx	79 (80.1)	67.4 (62.7)	31 (26)	87.2 (88.4)	87.3 (87.2)
Hispanic/Latinx	3.4 (3)	4.6 (2.5)	10.9 (8.1)	1.6 (1.5)	3.2 (2.1)
African American and Black	1.8 (1.7)	5.7 (3.8)	1.6 (1.0)	1.5 (1.2)	0.5 (0.4)
Asian and Native Hawaiian/ other pacific Islander	6.9 (6.8)	12.3 (17.0)	43.2 (52.2)	1.1 (1.2)	3.3 (3.8)
Percent American Indian/ Alaska Native	0.5 (0.4)	0.9 (0.5)	0.5 (0.5)	0.7 (0.5)	0.8 (1.0)

[1]*IPEDS data retrieved from: https://nces.ed.gov/ipeds/datacenter/Data.aspx*
[2]*University pseudonyms follow those given in [8]: LPU1 and LPU2, large public universities; LPrU, large private university; PTU, public technical university; PTI, private technical institute.*

Table 1.
Percentage of bachelor's degrees earned in 2009 (percentage of bachelor's degrees earned in STEM fields in 2009 in parenthesis).[1]

stereotypes of women and students of color not being as good at or as interested in STEM as white, Asian, and male students [15].

An anti-deficit interpretation rejects this assumption and rather assumes (1) that women and students of color can thrive in STEM, (2) that the disproportionate enrollment of white and Asian students, and disproportionate persistence of men indicate a failure of the system and not of the students, and (3) we can learn how to better support women and students of color to thrive in STEM by studying the women and students of color who are already thriving in STEM [16].

The enrollment and persistence data indicates that the five schools we visited, and that we based our "features of successful calculus programs" (which have come to shape improvements to calculus programs across the country) were based on programs serving a predominantly white and Asian, male student population. That is, the demographics of the students in these calculus programs were predominantly white and Asian men and women students, and the students persisting through the sequence were disproportionately men of all races and ethnicities. Knowing this information and coming from an anti-deficit perspective, I argue that the seven features can only offer possible improvements for calculus programs when considered in conjunction with diversity, equity, and inclusion practices. Diversity practices refer to actions done within the calculus program and mathematics department that attract and retain a diverse population of students. Equity practices refer to actions that (1) acknowledge the multiple ways in which some people face barriers (both visible and invisible) to their success, and (2) work to dismantle these barriers [17, 18]. Inclusion practices refer to actions that support the full participation of a diverse student population within the classroom community and within the broader departmental and institutional communities. By focusing on the original seven characteristics alone, departments may foster inequities by further supporting the populations of students who are already successful in calculus. Instead, departments should explicitly implement diversity, equity, and inclusion practices while also improving their programs through focus on the seven characteristics.

As a follow-up project to CSPCC, the PtC project has identified 12 research-oriented mathematics departments implementing a combination of the seven features in the Precalculus and calculus programs. For the PtC project, we used IPEDS data to very purposefully consider the demographics of the students enrolled at the schools, and the demographics of the students graduating with STEM degrees, when selecting the 12 institutions involved in our study. This resulted in a number of institutions serving a more racially and ethnically diverse student population, and with a few of those institutions implementing programs specifically designed to support women and/or students of color and/or first-generation students to be successful in STEM. This work is ongoing, and we are in the process of learning more about these programs so that we can share more about them with others schools. One disappointing finding in our recent work has been the general lack of programs geared to increasing the diversity in STEM among research-oriented math departments across the country; while there were programs at the university and college level developed to foster diversity, equity, and inclusion in STEM, there were very few programs at the department level [19].

3. An example of a college calculus program affords an anti-deficit perspective

Through the PtC work, I hoped to find a mathematics department where the calculus program was thoughtfully crafted to best support today's college students – a more diverse population of students, that includes more students of color, and more first-generation and low-income students than before [20]. We did not find a program that had an explicit focus on supporting a diverse population of students to thrive in mathematics, but we did see a calculus program developed to support every student in their construction of mathematical meanings in calculus. This program was developed based on research rooted in radical constructivism, and not with an explicit attention to equity. However, I believe this program affords an anti-deficit approach to mathematics by viewing every student's mathematical understanding as valuable and part of the construction of richer mathematical meanings. This calculus program illustrates that by sincerely valuing every student's mathematical understandings, and leveraging research to support each student's rich construction of mathematical meaning, a diverse population of college calculus students can mathematically thrive.

3.1 Background on DIRACC

Project DIRACC (*Developing and Investigating a Rigorous Approach to Conceptual Calculus)* is an NSF-funded college calculus curriculum developed by Pat Thompson and his colleagues based on years of research on student understandings of calculus (see [21] for a description). This curriculum is self-described as "Newton meets Technology", focusing on developing meaning for infinitesimals (while utilizing animations and interactive apps) rather than emphasizing the notation and formality of Leibniz. This curriculum is shared online for free, and is currently being implemented in at least two large, public, doctoral granting mathematics departments, including one involved in Progress through Calculus.

In this chapter, I will draw on my experience at the one university involved in PtC (referred to as Large State University; LSU), where DIRACC is the curriculum used for all calculus courses for science, computer science, and mathematics majors. The undergraduate population of LSU is approximately 50% white students, 20% Hispanic and Latinx students, 7% Asian, and 5% Black and African American. In the DIRACC calculus courses I observed, I estimated that approximately 30% of students were Black, Latinx, and/or Native (based on appearance). At LSU, there is a separate (and more procedurally oriented) college calculus course for engineering majors. The DIRACC courses are taught by instructors, mathematics education faculty, and doctoral students pursuing degrees in pure and applied mathematics and mathematics education. This course is coordinated by a full-time instructor, and this coordination includes weekly meetings for all instructors, where the topics of discussion during the meetings include understanding the mathematics and student thinking related to the mathematics for the upcoming section. Preliminary results from PtC indicate that students in DIRACC outperform students at comparable universities on a calculus content assessment and maintain positive beliefs towards mathematics more than students at other institutions.

3.2 Shift in curriculum

To best serve the students in our calculus classes, we need to learn what is motivating them to pursue degrees requiring calculus – whether future career goals or general interest in learning – and rethink our calculus curriculum to be in line with these interests. It is well established that in today's economy, STEM jobs pay significantly more, on average, than non-STEM jobs [22]. Given this widespread knowledge, we cannot ignore that one contributing motivation for students to pursue STEM is future job and wage prospects. When sitting in Calculus I classes across the country, it often seems that everyone knows the students are there not to learn deep and interesting mathematics, but to get a grade in the course that allows them to continue pursing whatever STEM degree they are hoping for in order to get a good job. I believe that we are missing a big opportunity in our calculus classes to inspire these STEM-intending students about the magic and beauty of calculus. The great majority of calculus courses I have visited have been "mainstream" courses, meaning to serve all STEM students, although in actuality the great majority of the content is driven by the needs of the engineering students, with occasional word problems being set in other contexts.

In a forward-thinking calculus system, there would be a meaningful connection between the content taught in calculus, the needs of the majors whose students are taking calculus, and the interests and motivations of the students enrolled in our courses. It would be these latter two driving the content, rather than historical precedents. The DIRACC curriculum achieves this by forgoing Leibniz's precise notation in favor of Newton's more intuitive ideas – skipping the formalities of ideas such as limit to spend more time supporting students to understand the ideas of infinitesimals and how this can support meaningful understanding of rate of change functions and accumulation functions. This curriculum was designed explicitly to support students in developing rich mathematical meanings, and is thus inherently responsive to how students think about calculus and what todays' students should be learning in a calculus course. As currently taught, I witnessed this curriculum equitably engaging a racially diverse student population in rich mathematics. This curriculum could go further in the future by engaging the diverse learners as whole people, by situating the mathematical content in contexts that are especially interesting and relevant for them (where these contexts could be identified by talking to students and using local data to identify trends in women and students of color's majors).

3.3 Shift in pedagogy

Through PtC, I observed three DIRACC calculus courses at LSU, and though the three courses looked different, in each I witnessed a racially diverse group of students equitably engaging in rich mathematics, contributing to constructing mathematical meaning as a class. In one class, the instructor stood in front of a 40-person class, while he randomly selected students to answer questions related to a context problem they worked on. The questions he asked were substantive and open ended, allowing every student to contribute thinking related to the question rather than simply answering correctly or incorrectly. The second class was a 120-person class where the instructor presented a slide presentation wearing a microphone, with three Learning Assistants circulating the room, and students discussing problems in small groups. The third class was a 30-person class where students spent the entire class working in groups of three-four on rich tasks while the instructor floated around the room, visiting with individual groups, and then bringing the class together for a whole-class discussion. The common element of these courses, in addition to the content being taught, was that the instructors authentically cared to understand what their students were thinking related to the mathematics, and that the instructors used this understanding of their students' thinking to connect the mathematics to the students' understanding of the mathematics – what Hackenberg has called exhibiting mathematical caring relations [23]. The DIRACC curriculum and its enactment at LSU illustrate a forward-thinking calculus program by centering the mathematics, and every individual student's construction of the mathematics, as the guiding forces.

4. An example of the process to develop an anti-deficit college mathematics program

As noted, the DIRACC curriculum was not developed with an explicitly focus on equity, though it affords an equitable enactment. Here, I provide an example of a college Precalculus program developed with an explicitly focus on changing the program to better support a diverse population of students. This example comes from a mathematics class designed at Bates College to prepare students for calculus, called *Mathematics Across the Sciences.* Meredith Greer described the development of this course in depth in a recent *PRIMUS* article called "Interdisciplinarity And Inclusivity: Natural Partners in Supporting Students" [24]. I will summarize some key aspects of this course and its development, but encourage interested readers to read the article for more details.

A group of mathematics faculty at Bates College developed this new course mainly informed by (1) input from faculty from every science department on their campus, (2) a multidisciplinary group of faculty focused on diversity and inclusion, and (3) mathematics education research and national conversations. Input from science faculty was gathered primarily based off meetings centered on which concepts they teach draw significantly on mathematics and what mathematical topics they want their students to know better. After meetings with all science departments on campus, trends surfaced which were used to guide the content of the course. One or two faculty members from each department then came together to refine the topics and include examples from their own fields. After the content was decided on, presentations were made to science and mathematics department chairs and faculty. While the interdisciplinary group worked together on the content, another interdisciplinary group of faculty was working together on learning how to support diversity and inclusion on their campus. This group was supported by the college and motivated, in part, by the Association of American Colleges and Universities (AAC&U) Making Excellence Inclusive project (which offers many very useful resources for departments interested in diversity and inclusion). This group primarily leveraged research on student experiences in higher education, especially the experiences of students of color, as well as the resources from the AAC&U Making Excellence Inclusive project. Based off these readings, the work developed pedagogical strategies that could be used across campus. These were then translated to the mathematics course being developed, resulting in a number of new pedagogical strategies. Lastly, the group developing this course also read and brought in recommendations from national mathematics education conversations, including the Mathematics Association of America's Curriculum Foundations Project [25] and the Inquiry Based Learning community [26].

Informal conversations with students were also used to understand more about their program, especially among the faculty group focused on diversity and inclusion, but not as directly as with the science departments. Input from students, primarily from student evaluations but also from informal conversations, was used to make improvements to each future iteration of the course (which in 2018 had been offered three times).

Greer describes how these components came together to inform the development of the course curriculum and the pedagogical approach: "Class time, course topics, and out-of-class assignments are designed to encourage a diverse set of students to succeed in this course as well as when they later proceed to more advanced mathematics and science courses" ([24], p. 2). This quotes perfectly reflects what should be the guiding principle of all college calculus programs, and can be cultivated through shifts in both the curriculum and the pedagogical approach: A forward-thinking calculus program is developed so that calculus courses, including the class-time, course topics, and out-of-class assignments, are designed to support a diverse set of students to succeed in the course as well as in courses building on calculus and in their STEM careers.

5. How such a program relates to the seven features of successful college calculus programs

Based on our site visits to five doctoral-granting mathematics departments with college calculus programs which we identified as more successful than other programs, we identified seven features of college calculus programs that we hypothesize are related to these programs' successes [13]. In [14], I discuss how each of these features can be thought of while implementing diversity, equity, and inclusion practices. Here, I consider how the above articulation of a forward-thinking calculus program would relate to the seven characteristics.

By my definition above, a forward-thinking calculus program is designed so that all components of the course support a diverse population of students to thrive. A diverse student population will include a diversity of mathematical backgrounds and experiences, cultural diversity, language diversity, as well as diversity of genders, ages, races and ethnicities, sexual orientations, and physical and mental abilities. While each of these types of diversity can influence the design of a forward thinking calculus program, here I foreground the role of diversity in mathematical backgrounds and cultural diversity.

A rich and engaging calculus curriculum designed to support a diverse population of students to thrive would acknowledge the needs of the students taking the course, including what additional mathematical preparation they need to thrive in the course and what components of calculus are needed in their future courses and careers. At my own institution, the calculus coordinator is often surprised and disappointed by calculus students' algebraic knowledge – one example is how persistent many students' belief that

$$a^2 + b^2 = (a + b)^2. \tag{1}$$

One way to respond to this realization is to blame the students for not being prepared enough, and to continue assessing their calculus learning by inherently relying on their lacking algebraic understanding, resulting in believing that the students also lack calculus understanding. A different way to respond to this realization is to blame the system responsible for educating these students, and either infuse algebraic lessons in to the calculus lessons or to not rely on students' algebraic skills for them to demonstrate their calculus understanding (for example, by not assigning algebraically messy functions and by delegating algebraic manipulations to technology). A forward-thinking calculus program would additionally learn what majors the students are pursuing and what calculus content students need to thrive in those majors – while STEM is constantly developing and growing, as should the mathematics we teach students to support them in STEM.

A mathematics department engaging in bringing their calculus program into the modern day should use *local data* to inform these changes. The types of local data collected can include quantitative outcome measures (such as grades and persistence) and qualitative measures of experience (such as focus groups with students who have persisted and those who have not). The value in the quantitative data is that it can identify trends and patterns and can be used to examine the prevalence of an observation. One downside is that the experiences of the majority can overshadow the experiences of the minority, and when designing a calculus program to support a diverse population of students to thrive, it is the voices of the minority that become especially important. Qualitative data can complement the quantitative data by illuminating experiences of a smaller number of students. One way to gather such data is to hold a number of focus group interviews with students (as done in the bates College example previously discussed), especially students from demographic groups and with experiences not held by the majority of the population. This could be holding a focus group of students of color in calculus to identify how they are experiencing the calculus program, and specifically how they are experiencing the calculus program as students of color. A similar focus could be taken by speaking to transfer students, first generation students, "non-traditional" students (typically older than traditional students), and students who have not taken calculus before. The quantitative and qualitative data gathered can be used together to inform curricular decisions (what do our students need from this course?), pedagogical decisions (what have students been experiencing in our courses, and what needs to change?), and programmatic decisions (is this calculus program achieving the goals that we want it to?).

Coordination of a calculus program designed to support a diverse population of students to thrive raises questions about what is fair. A primary goal of coordination is to ensure that all students (including those being taught by different instructors) experience a similar course and that their grades reflect this objectively. This need for similarity and objectivity speaks to a desire for the course to be fair for all students, though this inherently assumes that all students are coming in with the same preparation and resources. By acknowledging that this is not the case, the role of coordination becomes not to ensure fairness but to ensure justice for all students. A fair coordination system will seek to ensure that students are graded as objectively as possible and that this grade is only based on their knowledge. A just coordination system will seek to ensure that all students are given an opportunity to communicate what they have learned – which may entail acting in ways that do not seem fair to other students.

The acknowledgment that not all students are entering college calculus with the same mathematical experiences, preparation, and resources has a significant affect on the role of *placement* into mathematics. During our site visits to the more successful college calculus programs, we observed placement systems designed to place students into the highest course in which students could be successful. A key component of a placement system that is able to place students in this way is to have multiple options for courses that acknowledge the differences in student experiences. In our more recent work, we have seen examples of a broadened variety of college calculus courses that acknowledge that students come into college calculus with different prior experiences. The majority of these courses focused on supporting students on the lower cusp of placing into calculus (as determined by a placement exam, standardized test scores, or high school grades), such as calculus infused with precalculus and co-calculus (see [27] for details about these course structures), though we did observe courses designed to support students at the higher end of the placement, such as in the accelerated calculus course developed to support students who had already been exposed to calculus in high school. Such course variations enable a placement system to give students the course options in which they can be successful.

Through CSPCC and PtC, we observed growing support of *active learning* in the calculus sequence. While the specific implementations of active learning vary (including partner talk, group work, whole class discussions, and student presentations at the board), the common underlying element is that these classes engage students in mathematical activity during class. To engage students in rich mathematics during class time in a way that supports all students to thrive involves deep attention to and care of the mathematics of the students rather than only of the textbook or the instructor [23]. Another way to say this is that instead of describing the classes as "student-centered" I would describe them as "student-thinking centered." Such classes assume that students make sense of mathematics differently from one another and differently from the textbook or the instructor, and that such differences do not make their meanings incorrect; rather, drawing out multiple mathematical meanings for one problem leads to richer discussion and a richer understanding of the content. Forward-thinking calculus programs value and leverage the diversity of ideas present in a mathematics class composed of a diverse student population by engaging students in rich mathematics, eliciting their meanings of the mathematics, and engaging with the students' meanings of the mathematics.

What I describe here as a forward-thinking calculus program is far different from my own experiences as a college calculus student, and likely far different from the experiences of the majority of novice college calculus instructors (including graduate students, post-doctoral fellows, and new faculty). With this in mind, it becomes even more critical to provide teaching preparation to novice instructors involved in the teaching of calculus. One critical need for such preparation is purely pedagogical – while secondary teachers go through years of pedagogical preparation and apprenticeship, new college instructors are often expected to learn on the job. An additional need, that becomes pronounced when teaching to a more diverse population of students, is to help novice instructors understand that their students are not all like them (and are not all on their way to an advanced degree in mathematics) and to value what these students bring to their class. One professional development experience that can support this is to look at student work in a non-evaluative way; by looking at student work to understand what the students do understand and how they are making sense to come to their solution, rather than evaluating how many points a solution earns, instructors can learn to appreciate the richness of their students' mathematical thinking.

The final component of a forward-thinking calculus program to consider is the *supports that exist outside the classroom* that are designed to support a diverse population of students to thrive. Through the CSPCC and PtC work, we have observed tutoring centers specific to calculus content and shared workspaces in the mathematics department for students to informally gather to work on calculus together. Through the sites we have visited, we have seen much value in these supports, with many students sharing how impactful they were to their learning. We have also seen a number of rich supports for students that reside outside the mathematics department; for example, a mentoring program for students of color in STEM and a tutoring center and gathering space for Native students in STEM. Such programs could be made richer with more of a partnership with the calculus programs. While the mathematics departments' main focus is on supporting students mathematically, there is an opportunity for calculus programs to acknowledge calculus students as multifaceted people, and identify existing supports on campus that the calculus program could integrate into.

6. Conclusion

My intention in writing this chapter has been to blend my observations as a researcher with my desires as a mathematics professor and as a human. Calculus was the course that both enticed me to love mathematics and almost convinced me that mathematics was not for me, or, more honestly, that I was not for mathematics. Articulating and envisioning a calculus program that is explicitly developed to support a diverse population of students to not simply exist or persist in calculus, but to thrive has rejuvenated me to be optimistic about the role that calculus can play in students' STEM education. There are many big questions that remain both unanswered and unasked, and I am excited for a diverse population of students to become inspired to ask and answer these questions by experiencing a forward-thinking calculus program.

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Chapter 11

The Role of Mathematical Modeling in STEM Integration and Education

Murat Tezer

Abstract

With the rapidly developing technology, the labor force of the society has changed direction, and in the age of informatics, creative engineering applications have come to the forefront. Accordingly, the education levels of the labor force were also changed. The science, technology, engineering, and mathematics (STEM) education model in most countries aims to teach science, mathematics, technology, and engineering in relation to primary, secondary, high school, and higher education. STEM education, which has an impact in our country in recent years, has an important role in acquiring new skills, supporting creativity, innovation, and entrepreneurship, gaining the ability to transition between professions and adapting to new occupations. Nowadays, technology is expected to have different skills from individuals who will work in different fields with rapid development. Also, different teaching strategies play a major role in STEM integration and training. One of them, mathematical modeling, is the process of analyzing real-life or realistic situation using mathematical methods in the most general sense. The idea that mathematical modeling cycles should be used in STEM education at all levels from primary to tertiary education has gained importance in recent years, since it increases the students' motivation towards the lesson and they learn better by concentrating their attention.

Keywords: mathematical modeling cycle, STEM, real-life problems, metacognition, learning strategies

1. Introduction

Because of the quality of teaching, students find mathematics very abstract and fear mathematics. Thus, there may be difficulties in transferring the information learned in the classroom to the daily life. The fact that the learning environments are teacher-centered and uniform can be one of the reasons why students have difficulty in implementing information in their daily lives. In this sense, the subjects taught in the course should be taught by different practices and activities in a way that is more meaningful and related to daily life. One of these activities, mathematical modeling activities, can be said to show the relationship between real life and its applicability to real life.

Mathematical modeling involves a complex process in which a problem state encountered in real life is formulated mathematically and solved with the help of mathematical models, and the solution is interpreted and evaluated in the real

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world [1]. In this process, mathematics is used to represent, analyze, predict, or otherwise make sense of real-world situations [2]. In mathematical modeling, the individual tries to create a mathematical model that will solve the problem that he/she encounters in real life or in the future. The model in question includes not only mathematical structures but also estimates, assumptions, and strategies for solution [3, 4]. In other words, the solution plan including the assumptions, estimations, and mathematical tools used to solve the problem is the mathematical model for the problem. In addition to being mathematically correct, the model should be meaningful and adaptable for real life. While solving the problem, the individual should also evaluate the meaning of the solution for the real world. All these processes and all the stages of problem-solving in addition to the individual model are mathematical modeling [5].

Science, technology, engineering, and mathematics (STEM) education with technology age is appeared in the twenty-first century; it plays an important role in shaping cultural and economic development, embracing innovation, caring about creativity and problem-solving [6]. Due to the benefits of STEM education on the development of countries, intensive efforts are being made to reach the desired level between STEM and science education [7, 8].

The United States Bureau of Labor Statistics (2009) stated that 80% of the professions will need technology in 2018, and 8.5 million workforce will be needed in the STEM disciplines. STEM training can help students become problem-solvers and innovative and technologically literate citizens [9]. As the society becomes more dependent on technology, engineering, and mathematics, it is becoming increasingly important that students receive an integrated STEM education.

Due to global developments in the world demanding the thinking skills necessary to create a high workforce in the future, the curriculum for inter-curricular education in schools has been implemented. Initially, the implementation of STEM training was carried out with projects outside the formal classes. However, in the STEM education integrated with the direct curricula like Finland, there are also countries where many disciplines are taught.

STEM training has been implemented in many countries of the world (Korea, Japan, Germany, China, etc.), especially in the United States (USA) and in secondary schools and universities starting from primary schools. As STEM Education Coalition, there are organizations that undertake a roof in STEM education and direct STEM education and develop policy in this context [10].

STEM training, based on the integration of the disciplines of science, technology, engineering, and mathematics, has emerged as a result of the efforts of integrating separated parts in the real-world context [11], because, only by eliminating and integrating the boundaries between disciplines can the complex problems encountered in real life be understood and overcome. [12]. With STEM-oriented activities, the aim is to solve the real-life problems with the applications of technology and engineering disciplines by using the scientific knowledge which is the product of the basic sciences [12, 13]. For this purpose, it is necessary to remove the boundaries between disciplines [14–16]. In other words, STEM education understanding can be structured in the context of real-life problems by establishing a relationship between disciplines and focusing on a certain discipline.

Nowadays, both the training and applications related to STEM have been widely used in the world. On the one hand, many people now agree on what STEM means, interdisciplinary studies, and the common uses of science, technology, engineering, and mathematics. However, Clark-Wilson and Ahmed [17] emphasized that mathematics was included in an integrated curriculum on how M should be interpreted. Therefore, mathematics educators have said that mathematics in STEM should be used more, not as a servant. Coad [18] emphasizes that the use of mathematics as a data presentation tool with its study may lead to discrediting mathematics. Although mathematics is an inevitable component of STEM activities, it is also emphasized in this study that it is important to evaluate mathematical success and participation.

One of the most important tools for transition to STEM education is mathematical modeling [19]. Model-eliciting activities (MEA) are mathematical modeling applications. Mathematical modeling applications are composed of concepts related to different disciplines by their nature [20]. There is not a single definition of mathematical modeling agreed in the literature [21]. Instead, there are definitions, explanations, or shared assumptions made by individual authors. According to Kaiser [22], mathematical modeling is seen as a creative process to interpret the results and make changes to the model in order to define, control, or optimize the situation in order to make the real-life situation meaningful.

One of the many challenges faced by educators is the ways in which complex solutions to unusual problems can be taught to the student in the context of STEM education. One of the tools for transition to STEM training is the MEA [23].

MEAs, which are integrated into curricula for students to solve complex and difficult real-life problems, force students to build models and encourage them to test their established models, and their theoretical structure is known as a kind of open-ended problem-solving activities based on mathematical modeling perspective [24]. In school mathematics, MEAs have the potential to allow students to use mathematics in a flexible, creative, and powerful way in the STEM field because MEAs support the development of mathematical literacy [25], productive trends in mathematics [26], and a deep and integrated understanding of mathematical content and practices [27]. In MEAs, students clearly document their thought processes, consider their limitations, and use science and mathematics knowledge in the solution of the problem [28, 29]. MEAs offer students the opportunity to work on complex real-life problems involving model development. A framework for quality STEM integration curriculum is linked to the structure of MEAs [30]. According to the framework, the curricula (a) will serve a meaningful purpose and an engaging context, (b) enable students to develop problem-solving skills and engineering designs, (c) allow students to have the opportunity to redesign and learn if they fail, (e) support student-centered pedagogy, facilitator, and cooperative learning, including teacher, and (f) are designed to promote communication skills and teamwork [31].

2. Real-life problems, mathematical modeling cycles, and STEM

One of the first schemes presented as an approach to mathematical modeling is Blum [32]. The mathematical modeling cycle here consists of the real situation and the real world, the mathematical model, and the results in two parallel sections. In the loop, problem-solving is often perceived as a guide for the real situation.

According to Lesh and Doerr [3], it is the basic elements that must be included in a mathematical modeling cycle. There are three basic elements in mathematical modeling (**Figure 1**). According to them, a real-world problem must be started in mathematical modeling. The students generally act in the framework of mathematics and logic with ideas that involve mathematical assumptions and approaches. Then, the mathematics used should be accurate and also in a logical way (**Figure 2**).

The mathematical modeling cycle commonly used in literature is developed by Blum and Leiß [33]. Similar to other models, a distinction is made between the real world and mathematics in this model. A prerequisite for this model is that students

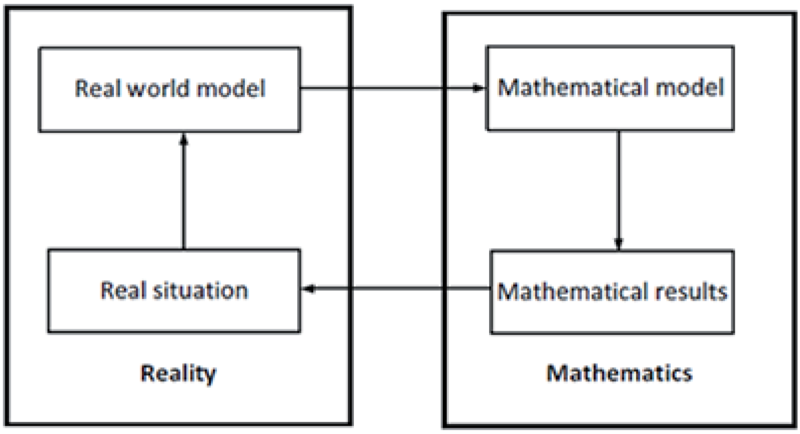

Figure 1.
Mathematical modeling cycle [32].

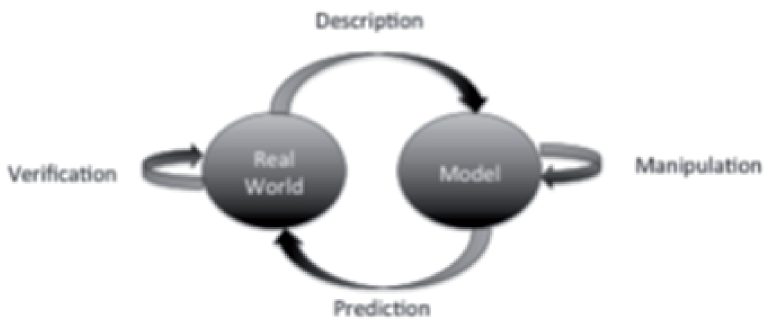

Figure 2.
Lesh and Doerr's modeling cycle.

should understand the mathematical problem and ensure that the model is developed in the real context. Although not mentioned here, it is important to keep in mind that the modeling process is in a repetitive natural loop (**Figure 3**).

Another important element is the existence of basic questions arising from the real-world problem in the mathematical cycle. These key questions can help to solve and study a mathematical modeling activity. Key questions are also very important for solving the problem. A key question can be shown as a real-life example of how long a person may be by spreading from the footprint and the length of the step [3]. Another feature of a key issue is that it allows people to focus on the issue. It can also bring people closer to their jobs or problems. The cycle of Perrenet and Zwaneveld is similar to that of Lesh and Doerr, but it has some differences. We observe that they provide more details and they emphasize three basic elements of mathematical modeling. In the modeling they describe, being outspoken and written communication are of paramount importance.

For example, students can conduct a mathematical modeling study and elaborate their solutions. Students also need to think through the modeling process so that they can clearly explain how well they understand the subject after a certain mathematical use. Thus, this mathematical cycle is repeated in a natural way. The revised solution is required during each cycle. This allows students to progress in different ways throughout the modeling cycle before developing an adequate solution. For the realization of such a process, they argue that the mathematical modeling activities of Perrenet and Zwaneveld must be open-ended (**Figure 4**).

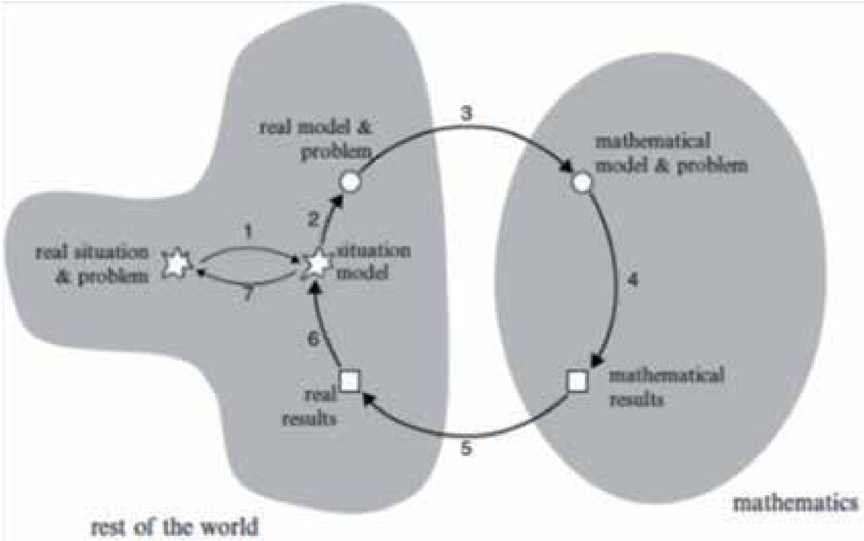

Figure 3.
Blum and Leiß [33] modeling cycle.

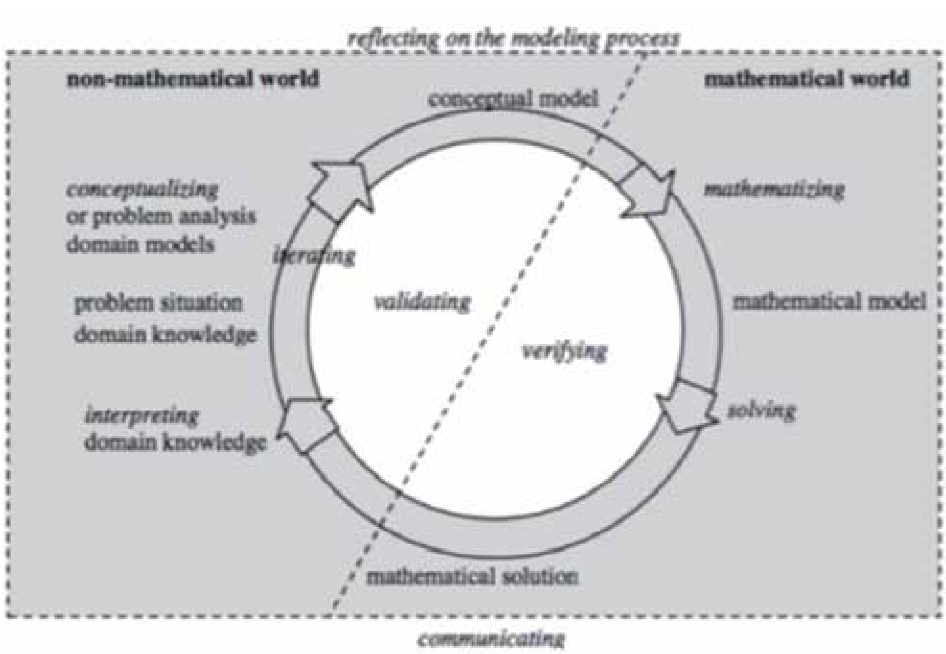

Figure 4.
Perrenet and Zwaneveld's modeling cycle.

Stohlmann and Albarracin [34] stated that there should be seven items in a mathematical modeling. The first one is that the problem should start with a real-world problem. Second, key questions should be addressed. The third one of these basic elements is the logical thinking of the solution of the problem with mathematical assumptions and approximations. Fourth, the mathematics used must be related to the real situation. The fifth of these elements plays an important role in written communication. The sixth, which is the mathematical modeling process, is an iterative process with open-ended problems. The seventh and last item is the reflections in the mathematical modeling used. However, the most widely used curricula are the modeling activities based on the models and modeling perspective.

For example, let us assume that there is an overflow after a heavy rainfall in a water-filled dam. Thus, in the case of an increase in the water level in the dam, the walls that protect the dam may break and the nearby city may cause a flood. This situation can be overcome by keeping the dam covers open at a certain time after each filling. As the precipitation continues, this situation will be constantly renewed. The important factors in this case are the water level in the dam, the amount of water discharged when the dam covers are open and the time. If necessary, a mathematical formula can be developed by considering the precipitation status for this problem. Even then, different variables or parameters can be found. The formulas that need to be considered here must be adjusted. For example, the amount, size, and time of the caps are important.

Some changes can be made in the model recursively. For such examples and similar representations, the example shown in the figure can be used as a mathematical model (**Figure 5**) [35, 36].

Güder and Gürbüz [38] aimed to improve the ability of interdisciplinary relations in the fields of mathematics, science, and technology in the field of "Energy-Saving Problem" for seventh grade students. In this problem, the concepts of power, motor power, power units (watt-kilowatt), and their transformation into each other are taught. In line with the purpose of the study, they tried to reveal the development of participants from a different perspective in a conceptually enriched environment in line with the multilayered teaching experiment [24, 39]. The multi-tier teaching experiment is designed to help students understand the modeling activities of teachers and teacher trainers in order to develop models for describing and explaining mathematical structures. The models are the teaching experiments consisting of three stages [24, 39, 40].

In this study, in the first 4 weeks of the study, thoughtful and supportive modeling problems are included. As a second step, the "Energy-Saving Problem" together with the Science teacher was developed by researchers. Finally, in the third stage, the researchers made observations and inferences during the application of the

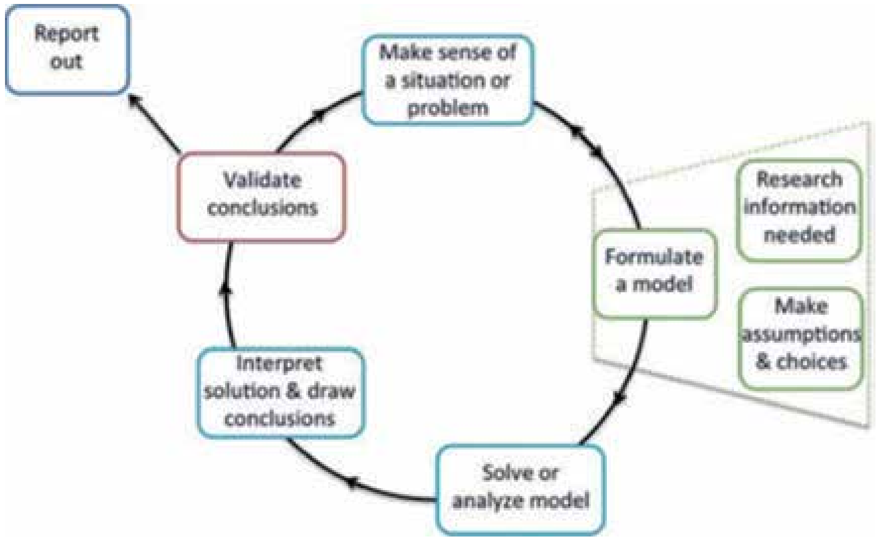

Figure 5.
A representation of the mathematical modeling process [37].

problem and reported the participants' progress in this matter. The general framework used in this study is as follows (**Figure 6**):

Real-life problems are discussed in mathematical modeling activities. Real-life situations are complex and cover many areas. Therefore, mathematical modeling is suitable for the different disciplines, and it is seen as an effective tool that can be used in STEM education [19, 41]. This type of activity, which is defined as interdisciplinary mathematical modeling (IMM), includes an understanding of different disciplines. In the understanding of IMM and in the solution of the problems of real-life situation, one or several disciplines are used together with mathematics [19]. In their study IMM is dealt with in mathematics and science. Therefore, IMM activities represent the activities associated with mathematics and science.

As mentioned above, the mathematical modeling process is a cyclical process consisting of several steps. Similarly, the IMM process is a cyclical and cascading process. However, unlike mathematical modeling, the inclusion of more than one area of IMM activities leads to a differentiation in the modeling process. Doğan et al. also defined a framework of the interdisciplinary mathematical modeling process for the mathematics and science disciplines in their studies. The IMM process begins in the real world, and first of all the individual needs to understand the real-life problem. The first step, which is expressed as an understanding of the problem, enters the STEM world.

A conceptual framework proposed by Daniels [42] was included in a study conducted on theories and assumptions developed before STEM training. This framework, which is designed as the theoretical framework of STEM integration, has been shown as three Venn diagram using mathematical modeling applications. While the first circle represents the elements of metacognitive theory (metacognitive knowledge, processes, skills, and strategies), the second circle includes social development theory (social mediated interaction—promoting communication). Lastly, the third circle consists of the teaching elements which are considered as basic for education.

If a good STEM integration is to be made, elements of the metacognitive [43] and Vygotsky's social development [44, 45] should also be included. As shown in

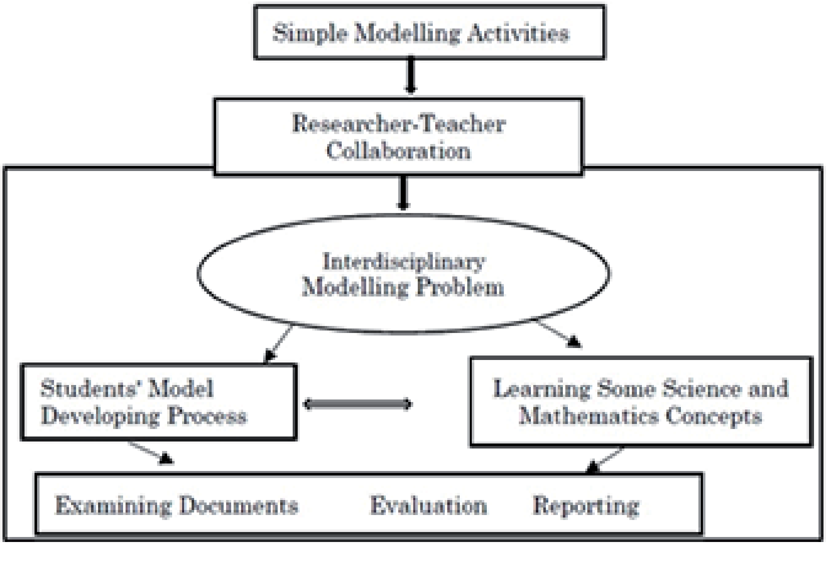

Figure 6.
Theoretical framework of the study.

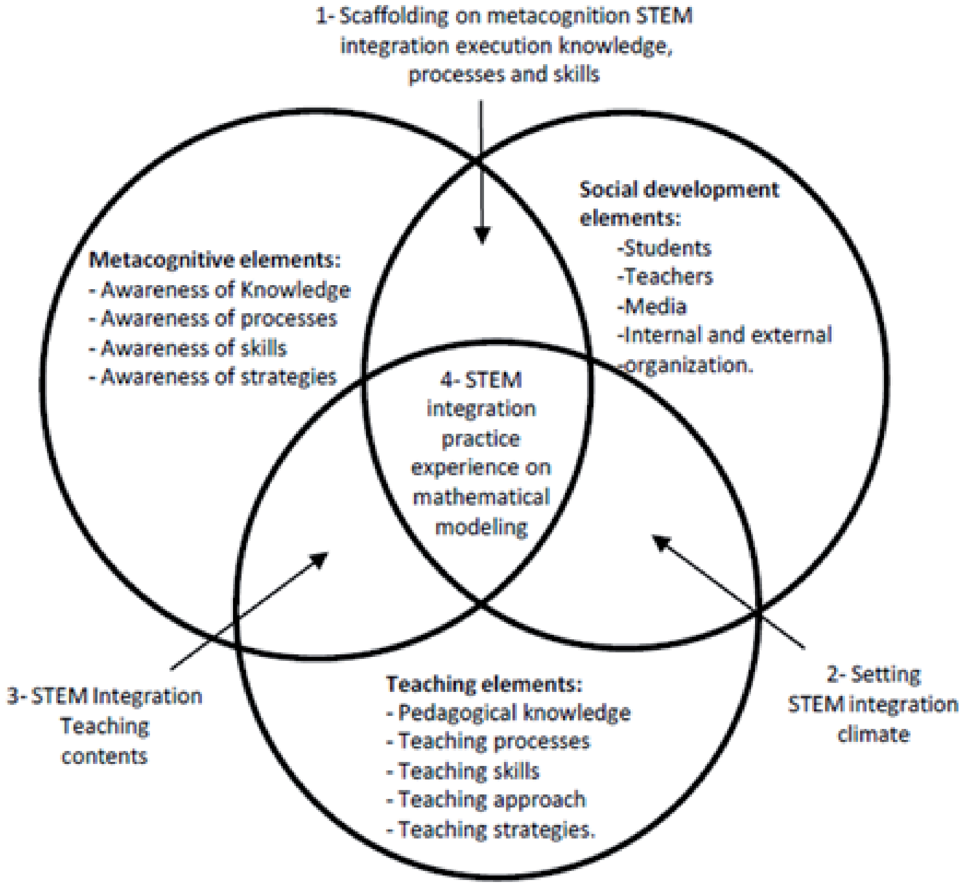

Figure 7.
The theoretical framework on metacognition of STEM integration from mathematical modeling perspectives.

Figure 7, STEM integration can be facilitated if the instructors implement these selected theories. These two theories have been proposed based on the following principles for implementation.

When Piaget [45], who explained the theory of cognitive development, explained only the characteristics of the cognitive development age stages, he mentioned the best level of learning and the importance of age for thinking development. Thus, Flavell's [47] theory (metacognitive knowledge, metacognitive experience, and metacognitive strategies) can explain the students' thinking, strategies, and actions to solve mathematical modeling problems [46, 48]. The problem-solving model of Polya may not be sufficient for a STEM practitioner [48]. This is because the problem is defined here in only three ways.

In particular, supporting mathematical and quantitative processes in science, mathematics, and engineering, and thus increasing mathematical reasoning, is the main objective. Technology provides tools to perform quantitative calculations more efficiently or to produce alternative visualization tools for experimental outputs. All modeling processes share the standard features shown in **Figure 8**. It has been demonstrated that there is a capability of researching modeling techniques, mathematical reasoning to model engineering design, and the ability to make scientific inquiry and then produce a structure. Mathematical modeling is of particular importance because it is important to produce appropriate tools to predict how quantification methods, new designs, and new situations will behave [49].

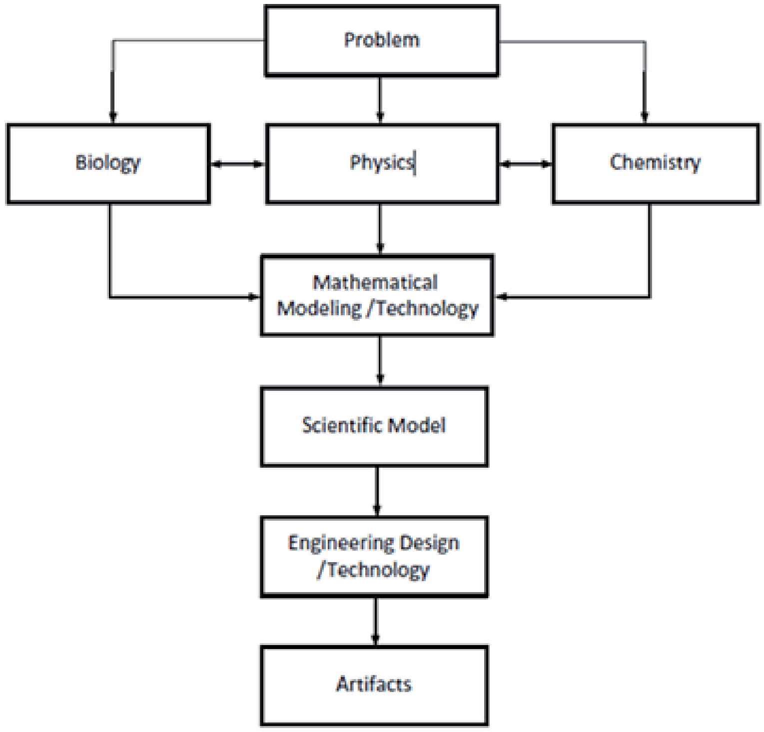

Figure 8.
Phases of STEM projects.

3. Discussion

Niss [50] stated that only theoretical mathematics knowledge is not always sufficient to solve real-life problems. In this case, the importance of mathematical modeling for the transfer of mathematical knowledge emerges. However, because the rapidly developing technologies and science are keys to solving real-life problems in different disciplines, STEM activities have been spread to schools. Thus, STEM integration has been added to the training program of many countries. In the educational programs of some countries, the presence of STEM activities combined with mathematical modeling also stands out [51].

Similarly, when questioning which stages of the mathematical modeling process improve students' problem-solving skills [49], the question of which stages of the "mathematical modeling together with STEM activities" should students use problem-solving skills raises too.

In the early 2000s, three and four stage cycles were used in mathematical modeling to solve real-life problems. However, over time, due to the need seen, these mathematical modeling cycles have been further elaborated by adding some steps. An example of this is Stohlmann and Albarracin [34] mathematical modeling cycle. Using science, technology, education, and mathematics together with mathematical modeling to solve real-life problems will facilitate to solve these problems [48]. Kertil and Gurel [52] and Sokolowski [49] supported this idea and were among the thinkers of STEM and mathematical modeling together. In the researches, teachers stated that this kind of instruction encourages students, focuses their attention on the subject and they learn the lesson better by leaving a positive effect on them [31, 53, 54]. An example of this is the STEM project conducted in conjunction with mathematical modeling to investigate the impact of student competences on sustainability in a university classroom [55]. In recent years, it has seen that teachers have been given courses for STEM training based on model-eliciting activities within STEM integration [30, 56].

4. Conclusion

When the studies are examined, more and more detailed explanations have been made about the cognitive activities in the modeling process. It is seen that technological developments are taken into consideration in the conceptualization of the mathematical modeling process. Considering the modeling used in the mathematical modeling process, the emergence of different frameworks and approaches reveals the complex structure of the process. For this reason, it is seen that the studies related to the mathematical modeling process, taking into account the different effects of technology, are combined with STEM, and this leads to the emergence of richer cognitive and metacognitive processes.

As a result of the importance of STEM activities in solving mathematical modeling and real-life problems in different disciplines, STEM activities continue to be integrated into schools. While many countries have added STEM to their education programs, some of them have been combining mathematical modeling with practices. Even teacher trainings on this subject are continuing.

As a result, it can be said that the teaching done by using mathematical modeling together with STEM increases the students' motivation toward the lesson; they learn better by concentrating their attention on the subject, leaving a positive effect on them; and the students' success and attitudes toward the lesson increase. Solving real-life problems in the future through STEM and mathematical modeling will continue to play an important role in providing innovative and creative problem-solving perspectives in the cultural and economic development of the countries.

Conflict of interest

The author declares no conflict of interest.

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Chapter 12

Discipline, Task and Reader Characteristics of Introductory Physics Students' Graph Comprehension in Mathematics and Kinematics

Itumeleng Phage

Abstract

Students' comprehension of graphs may be affected by the characteristics of the discipline in which the graph is used, the type of the task, as well as the background of the students who are the readers or interpreters of the graph. This research study investigated these aspects of the graph comprehension from 152 first year undergraduate physics students by comparing their responses to the corresponding tasks in the mathematics and physics disciplines. The discipline characteristics were analysed for four task-related constructs, namely coordinates, representations, area and slope. Students' responses to corresponding visual decoding and judgement tasks set in mathematics and kinematics contexts were statistically compared. The effects of the participants' gender, year of school completion and study course were determined as reader characteristics. The results of the empirical study indicated that participants generally transferred their mathematics knowledge on coordinates and representation of straight-line graphs to the physics contexts, but not in the cases of parabolic and hyperbolic functions or area under graphs. Insufficient understanding of the slope concept contributed to weak performances on this construct in both mathematics and physics contexts. Discipline characteristics seem to play a vital role in students' understanding, whilst reader characteristics had insignificant to medium effects on their responses.

Keywords: kinematics, algebra, graphs, interpret, coordinates, slope, straight line, parabolic and hyperbolic functions

1. Introduction

Graphic representation, a method used to show and represent values, increases, decreases, comparisons to either make predictions or show a report of how a certain situation was yesterday and how it is today, is an integral part of all scientific subjects. Scientific graphs visually communicate data and information about variables and their relationships and are often used in the analysis of data to determine patterns and relationships [11, 21]. Be that as it may, the specific purpose and usage of graphs may differ tremendously, even in subjects as closely related as mathematics and physics [19]. Graph comprehension is thus subject specific, that is, it depends on the discipline characteristics of different subjects [6].

According to Redish and Gupta [19], it is important that physical meaning of mathematical symbols is attached when applying mathematical knowledge in physics. Meredith and Marrongelle [14] further explain this by stating that we interpret mathematical concepts in the context of physics; hence according to Redish [18], the blending of the mathematics symbols, structures and rules with physics concepts, principles and laws is significant to students. This is because the blending will help students to solve kinematics/physics equations and interpret graphs. Woolnough [25] discovered that students tend to interpret slope as a mathematical quantity and that it cannot be associated with units as in physics graphs.

The researchers are therefore investigating in the empirical study why participants' performances on similar tasks in mathematics and physics graphs yielded different responses. There are few investigations on students' application of mathematics knowledge in physics [12, 25], whilst most studies focussed on problem-solving (e.g., [5, 18]) and specific aspect interpretation like slope of graphs [17, 25]. The researchers also found out that less study has been conducted in the four qualitative and quantitative constructs' tasks on the effect of discipline, task and reader characteristics in the mathematics and physics contexts and hence this study.

2. Theoretical background

2.1 Graph comprehension

According to Okan et al. [15], graph literacy is a necessary skill for decision-making, and it has often been neglected. Szyjka [24] citing Fry [7] defined "graphs as two-dimensional representations of points, lines and spaces, where data are displayed through represented words and numbers." A student can show comprehension of graph by being able to read and interpret it, that is, derive its meaning [6, 8]. According to Dori and Sasson [3] and Friel et al. [6], by working with graphs, students acquire graph sense and graphical thinking skills, and they are also able to comprehend the nature of graphs presented to them and are able to give variables and their relationships meaning [11]. Students acquire graph sense by working with graphs, and they gain graphical thinking skills and are also able to comprehend the nature of graphs as well as give variables and their relationships a meaning [11].

Scott [20] reported variation in students' performance in questions set on different levels in a questionnaire with corresponding mathematics and chemistry questions. He conducted a study on the participants' use of mathematics on the mole concept. No significant difference occurred in the participants' responses to the easier questions; however, the more difficult questions yielded a significant difference with better performances in the mathematics questions than the chemistry ones. He argued that algorithmic approaches in mathematics contribute to students' difficulties with calculations in chemistry.

Stahley [22] reported that even though students may have a correct idea or procedure to comprehend and illustrate discipline, task and reader characteristics of a graph [6], their confidence in taking such a decision is lacking. Some of them may understand the concept but lack the principles, and they seem unable to demonstrate the procedure. In physics graphs, physical contexts embed both algebraic and graphical representations [9].

2.1.1 Students' difficulties with kinematics graphs

McDermott et al. [13] investigated difficulties students experience with graphs as used in kinematics, and in their findings, state that the students seem to lack the ability to abstract information from the graphs. This cannot just be due to inadequate mathematics preparation, because often, students that are able to construct and interpret graphs in mathematics cannot do the same for graphs in physics. The difficulties they experience are rather because of an inability to make connections between graphical representations and physical ideas. The difficulties found by McDermott et al. [13] were divided into two groups: connecting graphs to physics concepts and connecting graphs to the real world.

Concerning the difficulties students experience in connecting graphs to physical concepts, McDermott et al. [13] found that students often do not know whether to use the value of the graph or the gradient of the graph to subtract the information from. This is referred to as the (function) value/gradient confusion. Students are also confused between changes in the value of the graph and changes in the gradient. Changes in value are easier to see than changes in gradient. As mentioned earlier, students see a constant graph as a graph with a constant gradient (linear graph). When constructing one graph from another, students find it difficult to ignore the form of the original graph. Many students do not have the ability to differentiate between displacement-time, velocity-time, and acceleration-time graphs. This can be due to the confusion between graph value and gradient and/or the inability to connect the physical concepts to the different features of the graph.

It was also found that students are not able to match the narrative information of the problem with the relevant features of the graph (McDermott, et-al. [13]). In the example used by McDermott et al. [13], the students had to determine the acceleration from a velocity-time graph over certain intervals. Many of them only used the coordinates of one of the endpoints of the line sector (y/x) instead of the change over the interval $(\Delta y/\Delta x)$, despite the fact that they referred to the acceleration as change in velocity divided by the change in time. They were also asked to determine the acceleration of a part of the movement that was not included on the graph. Most of those who determined the acceleration on the given interval wrongly calculated acceleration for the part not given on the graph. This shows that they did not match the narrative description of the problem with the graph correctly.

In physics, students have to determine the area under graphs before they have done integration in mathematics. Although they have calculated areas of many two-dimensional figures, the idea that the area under a graph can be used to determine a physical quantity is very new and strange to them (McDermott et al. [13]). The fact that, for example, the area under a velocity-time is displacement is memorised and used. They do not realise that the area under the graph represents the functional relation $f(x)\Delta x$ and that, for example, the area under a velocity-time graph is $\Delta s = v\Delta t$. They further do not associate a positive area with displacement in the positive direction and a negative area with displacement in the negative direction. When asked to determine the position at a certain instant from a velocity-time graph, students found it hard to understand that they have to determine the displacement over an interval.

Problems which can be solved by simple recall can be done with ease by most students (McDermott et al. [13]). Students find it hard to solve problems where the detailed interpretation of a graph is needed. To be able to use graphical interpretation to solve problems requires more than just memorization, for example, the gradient of the velocity-time graph is the acceleration and that a constant gradient on a velocity-time graph means constant acceleration.

To determine to what extent students connect kinematics graphs with the real world in the study of McDermott et al. [13], balls were released to roll down different inclines, and the students had to register the instant a ball passes a certain point. From that information, displacement-time, velocity-time and acceleration-time graphs had to be drawn. When constructing the displacement-time graph, many students indicated the displacement per time interval instead of the displacement at a certain instant, drawing discontinuous graphs. Others indicated the displacement at certain instances correctly but did not connect the dots to indicate continuous motion. The students also struggled to separate the actual path of the ball from the form of the graph. In one of the movements, the ball rolls up an incline and down again. Many students did not represent the velocity as negative, indicating the ball was rolling in the opposite direction. When drawing the acceleration-time graphs, most students did not realise that a positive (negative) acceleration does not necessarily means speeding up (down) the ball. They did not realise that when the ball was rolling up and down the incline, the acceleration was in the same direction. Many students also drew the displacement-time, the velocity-time and the acceleration-time graphs with similar shapes. They found it hard to accept that the same motion can be represented by graphs with different shapes.

According to a study done by Beichner [1] in which he used the Test of Understanding Graphs in Kinematics, similar difficulties and misconceptions were found. It was found that students struggled to determine gradient in the correct way especially if the graph did not run through the origin. Students considered the graph as a picture of the path followed by the object and not as an abstract mathematical representation of the movement. When answering the questions, the students did not distinguish between the variables' displacement, velocity and acceleration. As indicated above, they believe that the displacement-time, the velocity-time and the acceleration-time graphs have to look similar. Beichner [1] also found that the students did not recognise the meaning of the area under the different graphs. In the answering of many of the questions, the confusion between the graph value, the gradient and the area under the graph was clear.

Some of these misconceptions are caused by the fact that students do not connect what they learn in physics with their everyday experiences Brungardt and Zollman [2]. The difficulty students have with negative velocity can, in part, be because a speedometer only indicates positive speed. Students may associate the word "negative" with decreasing or lesser quantity. This then means that vocabulary also causes problems for the students. They use the word "constant" to refer to a linear graph with a constant gradient, whilstthe words "up" and "down" are sometimes used to indicate an increase or decrease of magnitude or to indicate direction.

3. Aim and research questions

3.1 Research aim

The aim of the research is to investigate how discipline, task and reader characteristics influence physics students' graph comprehension in the corresponding mathematics and kinematics questions. The participants were 152 willing first year physics students enrolled at the Central University of Technology, Free State (CUT) in South Africa.

3.2 Research questions

The following research questions were addressed in the empirical study:

- What characteristics of graphic tasks (reading coordinates, connecting representations and interpreting the area under and the slope of a graph) hamper the participants' performances in mathematics and kinematics?
- What is the role of discipline and reader characteristics on the participants' comprehension of kinematics graphs?

4. Research design and methodology

In order to address the research questions, a questionnaire was designed, consisting of two sections, one section focusing on kinematics graphs and the other one focusing on corresponding graphs in mathematics. The kinematics questions were designed using Beichner's Test of Understanding Graphs in Kinematics (TUG-K) model (1994). The questions were based on the reading of coordinates, connection of representations, understanding and calculating the area under a graph and the gradient of a graph. Mathematics section was comprised of linear functions and graphs, the required skills and knowledge to solve kinematics graphs and equations. Validation of the content of questionnaires was done by two academics in the same research field. The questionnaires were further piloted using 30 first year physics students enrolled at Central University of Technology, Free State (CUT). Thereafter, changes necessary in the questionnaires were then effected. The final questionnaire showed a reliability with the Cronbach's alpha coefficients of 0.69 in the kinematics section and 0.75 in the section on mathematics.

The pairs of kinematics and mathematics questions are attached as Appendices. The corresponding mathematics and kinematics questions were not identical in order to prevent similarities in students' answers based on recognition of graphs in questions in the two sections. Discipline characteristics further necessitated differences. For example, in kinematics graphs, the independent variable, time, can only have positive values, whilst positive and negative x-values can be used in mathematics graphs. Still, care was taken that the corresponding mathematics and physics tasks in the questionnaire require the same judgement and similar visual decoding (as shown in **Table 1**).

The results of the questionnaire were statistically analysed using effect sizes, because no random sampling (only available sampling) was done. Effect sizes yield important results in any empirical study and can be used to give the practical significance of such results [10]. In this study, comparison between differences in proportions for mathematics and physics successes were interpreted according to Cohen's effect sizes

$$w = \sqrt{\frac{\chi^2}{n}} \tag{1}$$

where n is the total number of participants and the χ^2-value with one degree of freedom is retained from the McNemar test [23]. This effect size determines whether there is a practically significant difference between the proportion of students who succeeded in answering the mathematics correctly and the proportion of students who succeeded in answering the physics correctly. The w-values are interpreted as follows:

- $w < 0.3$ is a small effect.
- $0.3 \leq w \leq 0.5$ is a medium effect.
- $w > 0.5$ is a large effect.

A w-value of > 0.5 indicated a practically significant difference between the two aspects considered. For this study, a small effect size indicates that the mathematics and physics questions were answered similarly, either both correct or both incorrect. A large effect size means that the mathematics and physics questions were answered differently, either the mathematics correctly and the physics incorrectly or vice versa.

Tasks	Task characteristic	Mathematics knowledge	Physics knowledge
1. Reading coordinates	Context	Coordinates in a Cartesian plane	Symbolic meaning of coordinates
	Visual decoding	Connecting a function value to the specified x (or t) value	
2. Connecting representations	Context	Algebraic and graphical representations of functions	Algebraic and graphical representations of motion. Differentiate between constants and variables
	Visual decoding	Recognise the form and expression of graphs	
	Judgement	Differentiate between features such as positive/negative gradient and symmetry around x/y axis	
3a. Area qualitative	Context	Comparison of areas of different geometric forms with the same base and height.	$s = \int v dt$=area under v-t graph for interval dt, $v = \int a dt$=area under a-t graph for interval dt.
	Visual decoding	Identify the geometric forms of the areas under the graphs	
	Judgement	Compare the geometric areas with the same basis and height.	
3b. Area quantitative	Context	Formulas for calculation of areas of different geometric forms.	$s = \int v dt$ = area under v-t graph for interval dt $v = \int a dt$=area under a-t graph for interval dt
	Visual decoding	Recognize the forms of the graphs and read from the graph features of the forms (e.g. length, width, height)	
	Judgement	Compare the areas of the figures	
4a.Slope qualitative	Context	Meaning of the gradient of a graph	$v = ds/dt$= gradient of s-t graph at time t
	Visual decoding	The steepness of the given line segments differ	
	Judgement	Compare the steepness of the line segments and connect it with the slopes.	
4b. Slope quantitative	Context	Formulas for calculation of gradient of straight-lines.	$v = ds/dt$=gradient of s-t graph at time t
	Visual decoding	Reading appropriate coordinates from the graph.	
	Judgement	Is the value of the gradient reasonable?	

Table 1.
Task characteristics of questions.

Effect sizes of the reader characteristics on students' performances in the mathematics and physics sections of the questionnaire were statistically determined using Cohen's effect sizes [4]. The characteristics evaluated were the participants' gender, their study courses and whether they completed school the previous year or two or more years prior to the study. A gap between school and university physics may prevent knowledge retention and consequently lower performances. The statistical results are interpreted as follows for differences in average percentages in the mathematics and physics sections:

Effect size of 0.2 shows a small effect.
Effect size of 0.5 is medium but observable effect.
Effect size of 0.8 is large, that is, the difference is of practical significance.

5. Analysis of task characteristics of questions in the two disciplines

Before the empirical results are discussed, the characteristics of the tasks set in the mathematics and kinematics contexts were analysed on the level of the participants. This implies that this analysis may differ for more or less advanced participants. For example, more experienced participants may distinguish characteristic features of graphs by visual decoding only and consequently may not need to explicitly perform judgement.

As indicated in **Table 1**, each task (e.g., reading coordinates, etc.) requires different mathematical and kinematics contextual knowledge, although similar visual decoding and judgement are to be performed in both the contexts. The first task, reading coordinates, is the simplest and requires only contextual knowledge and visual decoding. The other graph tasks require contextual knowledge, visual decoding and judgement.

It is important to note that the kinematics tasks can only be done if the mathematics contextual knowledge is transferred and integrated with kinematics knowledge. In the first task (reading coordinates), participants should have contextual mathematics knowledge of Cartesian coordinates and integrate it with kinematics knowledge about the variables of position (s), velocity (v), acceleration (a) and time (t). Conventionally, the independent variable t is placed on the x-axis and the dependent (s, v or a) on the y-axis. In the questionnaire items, participants needed to connect the proper dependent variable (function value) to a given independent variable, using visual decoding.

The second task (called connecting representations) requires mathematical knowledge of the graphical representation and formula of straight-line, parabolic and hyperbolic functions. In the kinematics questions, participants needed to recognise the mathematical formats and graph forms of the given expressions containing kinematics variables, instead of mathematical symbols. Proper understanding further requires insight that the given kinematics equations and graphs represent functions of time. Without having and integrating this contextual mathematics and kinematics knowledge, the participants will not know which visual decoding and judgement tasks to perform.

In order to accomplish "area quantitative" and "area qualitative" tasks (tasks 3a and 3b in **Table 1**) on kinematics, participants must recall the kinematics relation $s = \int vdt$. Then they should know from mathematics that the integral is determined from the area under a line graph. Blending these kinematics and mathematics knowledge elements should result in understanding that displacement in interval dt is $s = \int vdt$ = area under v-t graph. Only then can the participants perform the expected visual decoding and judgement tasks.

Requirements for successful execution of the qualitative and quantitative tasks on slopes (tasks 4a and 4b) are similar to those for area. From mathematics, participants should know the meaning and formula for calculating the slope of a graph and be able to attach the kinematics meaning to it, that is, $v = ds/dt$ = gradient of s-t graph at time t. Thereafter, the visual decoding and judgement required by the different questions can be performed.

For all tasks, the discipline characteristics of the question thus determine what visual decoding and judgement tasks have to be done. Inability to perform the correct contextual tasks is expected to prohibit execution of correct visual decoding and judgement.

6. Results

6.1 Results: reader characteristics

The number of students and the average percentages obtained by each group are given in **Table 2** for gender, **Table 3** for the last school year and **Table 4** for the faculty in which they are enrolled.

The effect sizes for differences between groups are medium (≥0.5) for gender, small for last school year and insignificant for faculty. In all cases, the effect size values were larger for mathematics than physics.

6.2 Results: task characteristics

Table 5 summarises the average percentages correctly obtained by the participants as well as the results of the McNemar test for each question pair (refer to Appendix). The questions are categorised in constructs according to the tasks to be

Gender	% of students	Mathematics Average %	Physics average percentage
Male	53.4	67.4%	38.3 %
Female	46.6	58.1 %	31.7 %
Effect sizes		0.58	0.52

Table 2.
Gender performances.

Last school year	% of students	Mathematics Average %	Physics average percentage
Previous	51.3	66.3	36.4
Before	48.7	59.3	33.4
Effect sizes		0.43	0.23

Table 3.
Performance by last schooling attended.

Faculty of study	% of students	Mathematics Average %	Physics average percentage
Humanities	23.1	60.7	35.2
Engineering and Information Technology	23.8	64.2	34.5
Health and Environmental Sciences	53.1	63.3	35.1
Effect sizes between pairs of faculties		≤ 0.24	≤ 0.07

Table 4.
Performances by faculties.

Task	Paired questions	Mathematics correct (%)	Physics correct (%)	*w*-value
1. Coordinates	M_C1 x P_C1	93.4	92.1	0.04
	M_C1 x P_C2	93.4	84.2	0.22
2. Representations	M_R1 x P_R1	67.1	65.1	0.03
	M_R2 x P_R2	72.4	29.0	0.58**
	M_R3 x P_R3	69.8	38.2	0.44*
3a. Area qualitative	M_A1 x P_A1	72.4	41.4	0.42*
	M_A2 x P_A2	69.1	27.0	0.63**
3b. Area quantitative	M_A3 x P_A3	56.9	29.6	0.43*
	M_A4 x P_A4	63.8	12.5	0.67**
4a. Gradient qualitative	M_S1 x P_S1	46.7	34.2	0.18
4b. Gradient quantitative	M_S2 x P_S2	82.9	64.48	0.30*
	M_S3 x P_S3	16.5	7.90	0.22

Table 5.
Results of the effect sizes for paired mathematics and physics questions.

performed, that is, reading coordinates, connecting representations, area (qualitative and quantitative) and slope (qualitative and quantitative). In **Table 5**, the label "*M*" is used for the mathematics questions, whilst "*P*" indicates physics (kinematics) questions. The percentages of participants who had the specific question correct are given in **Table 5** as well as the w-values calculated from the McNemar test, indicating the effect size of differences in responses. Medium effect sizes ($0.3 \le w \le 0.5$) are marked with a single star (*) and large effect sizes ($w > 0.5$) with a double star (**). Large effect sizes imply that the pair of questions were answered significantly different, that is, either the mathematics question correct and the physics incorrect or vice versa. The w-values that are not marked show a small effect size ($w < 0.3$), that is, the pair of questions were answered similarly, that is, either both correct or both incorrect.

Four additional physics questions aided in the interpretation of the results of **Table 2**. These questions are incorporated in the Appendix, and participants' performances are given in **Table 6**.

Task	Question	Percentage correct
Area qualitative	P_A5	53.5
Area quantitative	P_A6	51.7
Gradient	P_S4	48.7
	P_S5	59.2

Table 6.
Additional physics questions.

For all four tasks, the results (**Table 5**) show that participants performed better in the mathematics questions than the corresponding physics questions. Comparison of the average percentages and w-values between the tasks shows differences in how participants performed. Their responses thus seem to depend on the characteristics of the tasks, as discussed below:

6.2.1 Coordinates (task 1)

In task 1, the reading of coordinate values from the given graphs in the mathematics and physics contexts was assessed (questions M_C1, P_C1 and P_C2). The participants performed well in this task (>80% correct), and the low w-values (0.04 and 0.22) indicate consistency in responses, that is, the majority of participants answered correctly in both pairs of questions. It therefore, seems that the participants effectively transferred their mathematics knowledge about coordinates in a Cartesian plane to the kinematics domain. The lowest average performance (84.2%) obtained in the second kinematics question (P-C2) is probably due to the need to estimate the position (y) value by using the scale, which seems to be more difficult than reading values from intersections of grid lines as is the case in the other questions.

6.2.2 Representations (task 2)

In both sets of mathematics and physics questions on the representation task, five graphs of different forms were given (see Appendix). In the three pairs of questions, the participants had to match a straight-line, hyperbolic and quadratic function to one of the given mathematics graphs and linear motion equations to kinematic graphs.

The vast majority of participants knew that the mathematics function in item M_R1 is a straight-line graph and chose either the correct one, option 1 (67.6%), or the additional straight-line, option 2 (21.2%). With regard to the hyperbolic and parabolic functions g(x) in item M_R2 and h(x) in item M_R3, respectively, more than 70% of participants related each to the correct graphs. In both latter cases, the second largest contingent of participants (about 20%) connected the hyperbolic function to the parabolic graph or vice versa. These participants seem to confuse the representations of hyperbola and parabola in the mathematics contexts.

With regard to the physics items on this task, the largest correct percentage (65.1%) was also obtained for the straight-line representation (P_R1). The small w-value of 0.03 indicates transfer of these participants' mathematics knowledge to kinematics. For the hyperbolic and parabolic equations only, small percentages of participants succeeded (about 38 and 29%, respectively). The large w-values (0.58 and 0.44) imply medium to practically significant differences in responses to the mathematics and physics questions, indicating that participants who managed the mathematics tasks could not do the kinematics tasks.

6.2.3 Area qualitative and quantitative (tasks 3a and 3b)

The average percentages in the four mathematics questions on comparison or calculations of the area under graphs (M_A1, M_A2, M_A3 and M_A4) ranged from 56.9 to 72.4%. Higher percentages were obtained in the qualitative than the quantitative questions in the corresponding physics questions on area under kinematics graphs (P_A1, P_A2, P_A3 and P_A4), where the participants obtained low percentages ($\leq$40%), indicating that they did not apply their existing mathematics knowledge.

The w-values for the corresponding pairs of questions on area were all medium to large, confirming inconsistencies in the students' responses. Students who were successful in the mathematics contexts generally failed to transfer their mathematics knowledge to the kinematics context. Practically significant differences in answers were obtained when comparing qualitative questions M_A2 (largest area under graph) and P_A2 (largest displacement from v-t graph), as well as quantitative questions M_A4 (calculation of area under section of x-y graph) and P_A4 (calculation of change of velocity from an acceleration-time graph).

Possible reasons for the poor performances in the physics questions on the area were investigated by additional qualitative item P_A5 and quantitative item P_A6. In P_A5, the participants were asked whether displacement can be obtained from the area or slope of velocity-time or acceleration-time graphs. Only half of the students (53.5%) knew that the option "area under a velocity-time graph" is the way to determine displacement. Approximately a quarter of the participants chose the incorrect option "gradient of a velocity-time graph," showing area-slope confusion. The slope-area confusion was confirmed in the additional question P_A6 that assessed the participants' understanding of what task should be performed and how it should be performed to determine the displacement in a straight-line velocity-time graph over an interval starting at the origin. Only 51.7% had P_A6 correct, and a large number of students ($\sim$30%) indicated that they would calculate the slope making the same slope-area mistake as in P_A5. Both these additional questions indicate that a lack of physics conceptual knowledge contributed to participants' failure in the kinematics questions on area.

6.2.4 Slope qualitative and quantitative (tasks 4a and 4b)

Mathematics item M_S1 and physics item P_S1 required students' judgement of intervals where the slope and the instantaneous velocity (on a position-time graph), respectively, are the highest. In both questions, <50% of the students chose the correct answer. According to the small w-value (0.18), the majority of students were unsure in both the mathematics and physics questions. It seems as if a lack of mathematics knowledge and understanding of the concept of slope is transferred from mathematics to physics. This deduction was confirmed in the additional physics questions P_S4 and P_S5, in which the participants had to identify the intervals on a velocity-time graph, where the gradient and acceleration, respectively, are negative. The w-value for these two questions is 0.17, indicating that the participants who did not know where the slope is negative, did not also know where the acceleration of the v-t graph is negative. In both questions, the option chosen by the second-most participants was DE, the interval with both negative function values and negative slope. This shows that students struggle to discriminate between function values (velocity) and slope (acceleration), which corresponds to the height-slope confusion reported by McDermott et al. [13] and Beichner [1].

In both the mathematics and physics quantitative contexts, the students performed much better in calculating the positive slopes starting at the origin (M_S2 and P_S2) than the zero slopes in later intervals (M_S3 and P_S3). According to the *w*-values, these pairs of questions were answered differently with small to medium effect, that is, similar mistakes were made. A reason for the very weak performances (16.5 and 7.9% correct) in items with zero slopes may be that the students do not understand that slope is the ratio of the *change* in y-values to the *change* in x-values. This is evident from the result that the majority of students (66.4% in M_S3 and 57.7% in P_S3) chose option 3 in these items where y/x instead of $\Delta y/\Delta x$ is used for the slope. In the first pair of quantitative items (i.e., M_S2 and P_S2), $y/x = \Delta y/\Delta x$ is valid, and the majority of participants (82.9 and 64.5%) consequently chose the correct option, even though they might have made the same error. Furthermore, area-slope confusion and slope/height confusion occurred amongst some of the participants. It thus seems that deficiencies in understanding the concept of gradient in mathematics has been transferred to the physics graphs.

7. Discussion of results

7.1 Reader characteristics

Of the three reader characteristics evaluated (gender, last school year and faculty), none showed a practically significant difference in how the groups of students performed in the mathematics or the physics sections of the questionnaire. With regard to gender, male students outperformed female students in both the mathematics and physics sections with medium effect. Although the effects of the last school year were smaller, a larger effect was obtained for mathematics than physics. This result implies that students who had a gap of one or more year since their previous studies of mathematics performed observably weaker than those who did mathematics at school the previous year, although both groups performed badly in physics. An interesting result is the indifference of the faculty the students were enrolled in; engineering students performed similar to students from the humanities as well as from health and environmental sciences faculty.

7.2 Task characteristics

The characteristics, namely context, visual decoding and judgement, of the tasks in the questionnaire are analysed in **Table 1**, and the results of the empirical investigation thereof are given in **Tables 2** and **5**. The main trends that were revealed are now discussed.

In the mathematics questions, the majority of participants were successful on reading coordinates (>90% correct), connecting representations (~70% correct) and on qualitative and quantitative area tasks (~65% correct). These participants showed conceptual understanding and effectively performed visual decoding and judgement tasks in the mathematics contexts. However, the majority of participants struggled with the tasks on slope, seemingly due to lack of conceptual understanding of the mathematical concept and calculation of slope.

In the physics domain, the majority of participants transferred and integrated their correct mathematics knowledge and skills on the reading coordinate task (>80% correct) as well as the representation of straight-line graphs (65% correct). In all other tasks, the average percentage was 50% or below, that is, the majority of the participants could not perform the tasks successfully. It is therefore deduced that characteristics of tasks had an influence on the students' graph comprehension.

With regard to the task on reading coordinates, the participants successfully performed the required visual decoding skill in both contexts. In the physics context, they attached conceptual meanings (position and time) to the x and y coordinates on the Cartesian plane. This elementary task underlies all other kinematics graph tasks. A problem that a minority of participants experienced was to estimate a value using a scale.

In the mathematics questions on representation tasks, most students successfully performed the visual decoding task of identifying and connecting the form and the equation of the three types of graphs. However, some experienced problems to correctly judge which one of the two given straight-line graphs resembles the hyperbolic function f(x) and which of the two parabolas are represented by the quadratic equation h(x). Hyperbolic-parabolic confusion that occurred amongst a minority of students also reveals judgement errors.

The participants' mathematics knowledge and understanding of matching expressions to types of graphs were only transferred to the physics domain in the case of straight-line graphs. With regard to the physics questions on parabolic and hyperbolic graphs, the majority of participants probably did not recognise correspondences in the kinematics expressions or graphs with the standard mathematical formats. This visual decoding problem may be based on the contextual task error, namely lack of understanding that the given kinematic equations are indeed functions, that is, s(t) and v(t). Consequently, their responses in the physics questions differed with medium to practical significance from those in the mathematics domain.

The results on the area tasks indicate that the majority of participants have mathematical contextual knowledge related to areas of geometric forms and can execute the tasks of visual decoding (know what part on the graph is the area under the graph) and judgement (comparing the areas). In the corresponding physics questions, the participants firstly had to take the kinematics context of the questions into account before deciding what visual decoding and judgement tasks had to be done. The poor performance of the participants in the physics tasks indicated that they encountered problems in accomplishment of the contextual tasks. They seemed to lack knowledge and conceptual understanding of kinematics quantities and graphs, namely how to obtain the change in velocity from an acceleration-time and the change in position from a velocity-time graph. This knowledge deficiency was confirmed in the additional items on the area. Contextual difficulties in interpretation of the area under kinematics graphs were also found by Beichner [1], McDermott et al. [13] and Palmquist [16].

Although participants' responses to questions on calculations of the slope of a straight line starting at the origin were correct, the other questions revealed deficiencies in the basic conceptual understanding of slopes in mathematics, namely that slope is the ratio of the *change* in y-values to the *change* in x-values. This hindered success in both contexts (with practical significance) in the tasks on the qualitative comparison of magnitudes of gradients as well as the understanding and application of negative and zero gradients. In these tasks, function value/slope confusion occurred, which was also reported by Beichner [1] and McDermott et al. [13]. This can be a contextual task error, but since the same confusion was encountered in the corresponding mathematics and physics questions, it is here also considered as a judgement error.

Comparison of the performances in the corresponding mathematics and physics tasks shows the following main trends causing success or failure in the physics questions:

1. Participants have the correct mathematics knowledge and conceptual understanding and transfer it to the physics domain, for example, when reading coordinates.

2. Participants reveal the mathematics knowledge but lack the necessary physics knowledge and conceptual understanding, for example, in the kinematics tasks on area and slope, they seem not to know which kinematics relation to use and what to calculate.

3. Participants are unable to blend mathematics and physics knowledge, for example, they do not perceive the kinematic equations as quadratic and represented by a parabola or as a hyperbolic expression and graph.

4. Participants transferred their misconceptions or insufficient knowledge in mathematics to the physics domain. This is evident in the height-slope confusion, area-slope confusion and parabola-hyperbola confusions that occurred in both the mathematics and physics domains. Inaccurate knowledge of the slope as the ratio of change in variables was to a large extent transferred from mathematics to kinematics.

7.3 Discipline characteristics

The results indicated that the majority of participants have an understanding of the physics discipline characteristics with regard to the use of kinematics concepts as variables that can be presented as coordinates on Cartesian planes. In the physics tasks on reading coordinates, they attached symbolic meanings (position and time) to the x and y coordinates. They also recognised correspondences between a linear motion equation and the standard mathematical format for straight lines in a representation task. However, they seem not to have the insight that kinematics relationships can be represented as functions, especially with regard to quadratic (parabolic) and hyperbolic functions. In addition, students failed to attach physical meaning to the area under graphs and slopes of graphs in the kinematics contexts.

In order for the participants to solve the physics questions correctly, they did not only have to know the discipline characteristics concerning kinematics graphs but also the discipline characteristics of graphs in mathematics. There are practices that are similar for mathematics and physics, for example, using the Cartesian coordinate system and placing the dependent variable on the vertical axis. Also, concepts such as slope and area are calculated the same in both contexts. Discipline characteristics that differ are, for example, that in mathematics, variables are abstract and have no units, whilst in physics variables, area under graphs and gradients all have physical meanings and units. Another difference is that in mathematics, the horizontal axis has a positive and negative side, whereas in kinematics, the concept time as the independent variable is on the horizontal axis and starts from zero only. The latter difference probably contributed to the significant differences in students' responses on the hyperbolic and parabolic representations. The kinematics graphs only showed the parts of the hyperbola or parabola for which the x-coordinate (time) is positive, which might have prevented students from recognising the graph form.

From the results of this study, it is clear that if students know the underlying mathematics, it does not imply that they can use it in another context. There is no automatic transfer from the mathematics domain to the physics domain when using mathematics to solve a physics problem. For a student to be able to solve a certain physics problem, he/she has to know and understand the underlying mathematics as well as the physics concepts and principles. Only then they may be able to blend the knowledge effectively.

9. Recommendation

In the physics classroom, the students have to be taught how to use their existing mathematics to solve the problems at hand. The instructor has to revise the relevant existing mathematics as well as physics knowledge and draw analogies between aspects such as geometric figures, expressions and graphic representations of functions, etc. Differences in discipline characteristics need to be discussed with the students so that they understand the purpose and applications of graphs in the two contexts.

Further research can be conducted for follow-up years after specific interventions have been done to specifically address the problems identified. This questionnaire can also be used by other lecturers for research purposes or to test their students' abilities and identify areas of concern and come up with intervention strategies thereof.

It is thus recommended that lecturers of undergraduate introductory physics should emphasise the knowledge and skills of algebraic graphs in teaching and learning of kinematics, especially kinematics graphs. This will enable these students to collect data, analyse it, plot graphs and interpret graphs based on this knowledge and relate it to and show physics understanding and knowledge.

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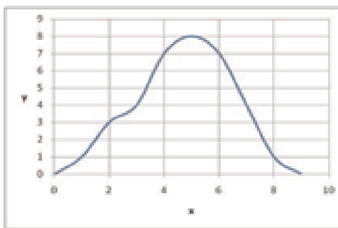
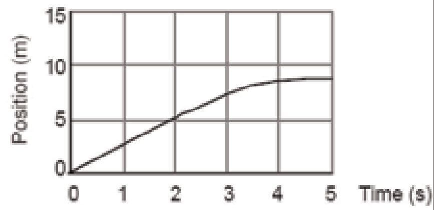
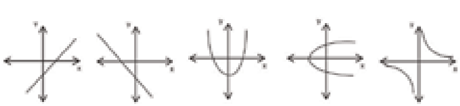
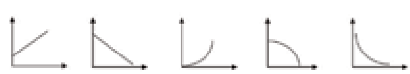
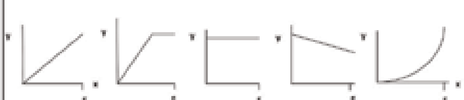
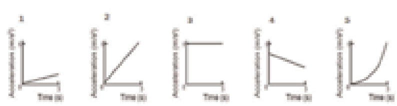
Appendix

Mathematics	Physics
Reading coordinates	
Use the graph below and answer the question that follows:  M_C1 What is the value of y if x = 4? 1 4 2 0 3 7 4 3 5 8	The position-time graph below shows the straight-line motion of an object. Answer the following questions:  P_C1 The position at the 2 second point in the position-time graph is most nearly: 1 0.4 m 2 2.0 m 3 2.5 m 4 5.0 m 5 9.0 m 6.3 The position at the 5 second point in the position-time graph is most nearly: 1 0.0 m 2 0.56 m 3 1.8 m 4 5.0 m 5 9.0 m
Connecting representations	
Choose the answers of the questions below from the following graph forms. 	Choose the answers of questions below from the following graph forms. 

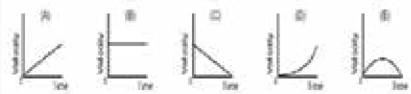
M_R1 Which one of the graphs shows the function $f(x) = x - 1$? 1 a 2 b 3 c 4 d 4 e M_R2 Which one of the graphs shows the function $g(x) = \frac{2}{x}$? 1 a 2 b 3 c 4 d 5 e M_R3 Which one of the graphs shows the function $h(x) = x^2 - 1$? 1 a 2 b 3 c 4 d 5 e	P_R1 What is the form of the v versus t graph if $v = u + at$ is plotted with u and a positive constants? 1 a 2 b 3 c 4 d 5 e P_R2 What is the form of the v-t graph if $v = \frac{s}{t}$ is plotted with s a positive constant? 1 a 2 b 3 c 4 d 5 e P_R3 What is the form of the s versus t graph if $s = ut + \frac{1}{2}at^2$ is plotted with u and a positive constants? 1 a 2 b 3 c 4 d 5 e
Area qualitative	
Choose the answers of questions below from the following graphs. In all these graphs the maximum values for y are the same.  M_A1 Which one of the graphs has the <u>smallest</u> area under the graph from x=0 to x=5?	. Five objects move according to the following acceleration versus time graphs.  P_A1 Which object had the smallest change in velocity during the three second interval? 1 1. 2 2. 3 3. 4 4. 5 5.

1 a
2 b
3 c
4 d
5 e

M_A2 Which one of the graphs has the <u>largest</u> area under the graph from x = 0 to x = 5?

1 a
2 b
3 c
4 d
5 e

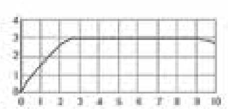
P_A2 Velocity versus time graphs for five objects are shown below. All axes have the same scale. Which object had the greatest change in position (displacement) during the interval?



1. (A)
2 (B)
3 (C)
4 (D)
5 (E)

Area quantitative

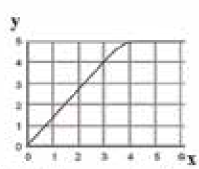
M_A3 Consider the following graph:



The area under the graph in the x-interval (4, 8) is:

1 0
2 1.33
3 4.0
4 12.0
5 24.0

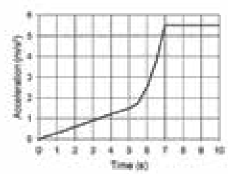
M_A4 For the graph below, answer the following question:



What is the area under the graph for 0 < x < 3?

1 0.75
2 1.33
3 4.0
4 6.0
5 12.0

The acceleration-time graph below represents the motion of an object travelling in a straight-line. Answer the following questions.



P_A3 What is the change in velocity of the object from 7 seconds to 10 seconds?

1 5.5 m/s
2 16.5 m/s
3 1.833 m/s
4 0.545 m/s
5 55.0 m/s

P_A4 What is the change in velocity of the object from 0 seconds to 5 seconds?

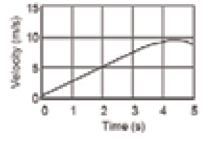
1 1.5 m/s
2 5 m/s
3 3.33 m/s
4 3.75 m/s
5 7.5 m/s

Area additional items

P_A5 Displacement can be obtained from the:

1 gradient of an acceleration-time graph
2 gradient of a velocity-time graph
3 area under an acceleration-time graph
4 area under a velocity-time graph

P_A6 If you wanted to know the distance covered during the interval from t = 0 s to t = 2s, from the graph below you would:



1 Read 5 directly off the vertical axis.

2 Find the area between that line segment and the time axis by calculating (5 x 2)/2.

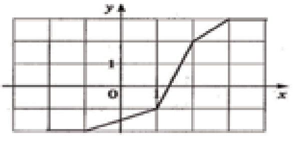
3 Find the slope of that line segment by dividing 5 by 2.

4 Find the slope of that line segment by dividing 15 by 5.

5 Not enough information to answer.

Gradient qualitative

M_S1. In which of the intervals is the gradient of the graph the largest?



1 -2 < x < -1

2 -1 < x < 1

3 1 < x < 2

4 2 < x < 3

5 3 < x < 4

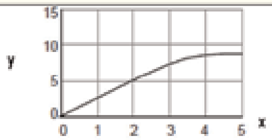
P_S1 Position versus time graphs for five objects are shown below. All axes have the same scale. Which object has the highest instantaneous velocity in the interval shown?

1 a
2 b
3 c
4 d
5 e

Gradient quantitative

What is the gradient of the graph when

The position-time graph below shows the straight-line motion of an object.

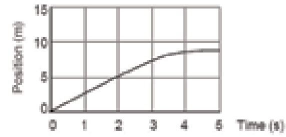


M_S2 x = 2?

1 0.4
2 2.0
3 2.5
4 5.0
5 10.0

M_S3 x = 4.5?

1 5
2 0
3 8 / 4.5
4 4.5 / 8
5 8



P_S2 The velocity at the 2 second point in the position-time graph is most nearly:

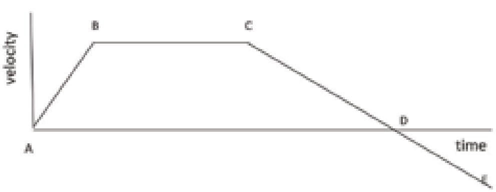
1 0.4 m/s
2 2.0 m/s
3 2.5 m/s
4 5.0 m/s
5 10.0 m/s

P_S3 The velocity at the 5 second point in the position-time graph is most nearly:

1 0.0 m/s
2 0.56 m/s
3 1.8 m/s
4 5.0 m/s
5 9.0 m/s

Gradient additional items

The figure below shows a velocity-time graph of an object's motion.



P_S4 Where is the gradient negative?
1 AB
2 BC
3 CD and DE
4 CD only
5 DE only

P_S5 Where is the acceleration negative?

1 AB
2 BC
3 CD and DE
4 CD only
5 DE only

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Chapter 13

Implementation of Elliptic Curve25519 in Cryptography

Intan Muchtadi-Alamsyah and Yanuar Bhakti Wira Tama

Abstract

Bernstein's design implementation of elliptic Curve25519 in key exchange is claimed to be highly secure and efficient. This curve is, for example, used in the key exchange scheme of TextSecure for Instant Messaging. In this paper, we present an implementation of elliptic Curve25519 in the simplified Elliptic Curve Integrated Encryption Scheme, thus showing that elliptic Curve25519 can also serve other purposes than key exchange. The curve is in Montgomery form, which makes it possible to use Montgomery ladder. Point compression, point decompression, encryption, and decryption algorithms are presented for the simplified Elliptic Curve Integrated Encryption Scheme.

Keywords: elliptic curve, cryptography, Montgomery ladder, integrated encryption scheme

1. Introduction

Curve25519 is an elliptic curve in Montgomery form with base field F_p and $p = 2^{255}-19$. In [1], Bernstein explains its design implementation, which is claimed to be highly secure and efficient. It is, for example, used in the key exchange scheme of TextSecure for Instant Messaging [2]. The advantage of using this curve is that for some point operations, we can use only the x-coordinate, which simplifies the computations and also saves storage.

In previous papers we have presented implementations of elliptic curves in Weierstrass form in a binary field: the implementation of a binary field arithmetic operation algorithm [3, 4] and the implementation of the simplified Elliptic Curve Integrated Encryption Scheme (S-ECIES) in a binary field [5]. In the current paper, we present the implementation of Curve25519 in S-ECIES, thus showing that Curve25519 can also serve other purposes than key exchange.

2. Elliptic curve Montgomery form

Before defining Curve25519, we will give some basic theory on elliptic curves. This paper is only concerned with elliptic curves in Montgomery form, not Weierstrass form. An elliptic curve over F_p in Montgomery form is defined by the equation.

$$By^2 = x^3 + Ax^2 + x, \tag{1}$$

where $A(B^2 - 4) \neq 0$.

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On the points of the elliptic curve, we may define point addition, negation, and doubling. We define point negation as follows: let E be an elliptic curve over F_p and point $P(x,y)$ be a point on E. We define point negation of P as $-P(x, -y)$. Let $P(x_1,y_1)$ and $Q(x_2,y_2)$ be two distinct points on E. Then the point addition is $P+Q$ (x_3,y_3), where

$x_3 = (\lambda^2 - A - x_1 - x_2), y_3 = \lambda(x_1 - x_3) - y_1$ and $\lambda = (y_2 - y_1)/(x_2 - x_1)$. If $P = Q$, then the doubling point $P + P$ is $2P(x_4,y_4)$, where

$$x_4 = (\lambda^2 - A - 2x_1), y_4 = \lambda(x_1 - x_4) - y_1 \quad (2)$$

and $\lambda = (3x_1^2 + 2Ax_1 + 1)/(2By_1)$.

The points on the elliptic curve along with point at infinity O form a commutative group with point addition as its operation.

We define scalar point multiplication as follows: given a positive integer m, scalar point mP is defined by $mP = P+P+...+P$ (m times addition of P).

The advantage of using Montgomery form rather than Weierstrass form is that in Montgomery form, it is possible to operate without y-coordinates.

Elliptic curve operation in Montgomery form without y-coordinates can be done as follows [6]: let $(X:Y:Z)$ be the projective representation of point $P(x,y)$ in E, define $nP = (X_n:Y_n:Z_n)$, and write (x,y) as $(X/Z, Y/Z)$. It is clear that $(m+n)P = mP + nP$. If $P_m(x_1,y_1) = mP$ and $P_n(x_2,y_2) = nP$, $x_1 = X_m/Z_m$ and $x_2 = X_n/Z_n$, then point addition is P_m+P_n $(x_3,y_3) = (m+n)P$, where $x_3 = X_{m+n}/Z_{m+n}$ and

$$X_{m+n} = [(X_m - Z_m)(X_n + Z_n) + (X_m + Z_m)(X_n - Z_n)]^2 \quad (3)$$

$$Z_{m+n} = [(X_m - Z_m)(X_n + Z_n) - (X_m + Z_m)(X_n - Z_n)]^2 \quad (4)$$

Point doubling is $2P_n(x_4,y_4) = 2nP = P_{2n}$, where $x_4 = X_{2n}/Z_{2n}$ and

$$X_{2n} = (X_n + Z_n)^2(X_n - Z_n)^2 \quad (5)$$

$$Z_{2n} = (4X_nZ_n)\left[(X_n + Z_n)^2 + (A-2)/4 * (4X_nZ_n)\right], 4X_nZ_n = (X_n + Z_n)^2 - (X_n - Z_n)^2 \quad (6)$$

Based on the work by Okeya and Sakurai reported in [7], we can recover the y-coordinate in projective coordinates. Let $P(x,y)$, $P_1(x_1,y_1)$, $P_2(x_2,y_2)$ be points on a Montgomery-form elliptic curve. Express $P_1 = (X_1/Z_1, Y_1/Z_1)$, $P_2 = (X_2/Z_2, Y_2/Z_2)$, and define X_1^{rec}, X_2^{rec}, X_3^{rec} as follows:

$$X_1^{rec} = 2ByZ_1Z_2X_1 \quad (7)$$

$$Y_1^{rec} = Z_2\left[(X_1 + xZ_1 + 2AZ_1)(X_1x + Z_1) - 2AZ_1^2\right] - (X_1 - xZ_1)^2X_2 \quad (8)$$

$$Z_1^{rec} = 2ByZ_1Z_2Z_1 \quad (9)$$

Assuming $P_2 = P_1+P$, then in projective coordinates the relation $(X_1^{rec} : Y_1^{rec} : Z_1^{rec}) = (X_1 : Y_1 : Z_1)$ holds.

3. Curve25519 and simplified ECIES

Curve25519 is the elliptic curve of Montgomery form

$$y^2 = x^2 + 486662x^2 + x \quad (10)$$

on F_{p2}, where p is the prime number 2^{255}-19. Based on Bernstein's paper [1], there are two subgroups of Curve25519 with large-size order, i.e., $\{O\} \cup \{E$

$(F_{p2}) \cap (F_p \times F_p)\}$ with size order $8 \times (2^{252}$ + 27742317777372353535851937790 883648493) and $\{O\} \cup \{E(F_{p2}) \cap (F_p \times \sqrt{2F_p})\}$ with size order $4 \times (2^{253}$–55484 63555474470 7071703875581767296995).

S-ECIES is based on the elliptic curve discrete logarithm problem described as follows [8]: let p be a prime number larger than 3. Let E be an elliptic curve over F_p such that E contains a cyclic subgroup H, generated by P, of prime order m. The plaintext space is $F_p{}^*$ and the ciphertext space is $(F_p \times F_2) \times F_p{}^*$. The key space is L = $\{(E, P, Q, n, m)$: $Q = nP\}$. Curve E and points P, Q, and m become public keys, and n becomes the private key.

For every $a \in F_p{}^*$ and a secret number $k \in [1, n-1]$, the encryption function is

$$e(a,k) = (\text{Point} - \text{Compress(kP)}, a.a_0 \bmod p) \in \left(F_p \times F_2\right) \times F_p{}^*, \quad (11)$$

where $a_0 \neq 0$ is the absis of kQ.

For every $(V, c) \in (F_p \times F_2) \times F_p{}^*$, the decryption function is

$$d(V,c) = c(x_0)^{-1}, \quad (12)$$

where (x_0, y_0) is the coordinate of Point-Decompress(V).

We know that the groups $\{O\} \cup \{E(F_{p2}) \cap (F_p \times F_p)\}$ and $\{O\} \cup \{E(F_{p2}) \cap (F_p \times \sqrt{2F_p})\}$ are finite with group size at $8 \times p_1$ and $4 \times p_2$, respectively, for some primes p_1 and p_2. Hence, E contains a subgroup with prime order; therefore, Curve25519 can be implemented in ECIES.

4. Implementation

In this section, we will give several algorithms in Curve25519 for implementation in S-ECIES, i.e., Montgomery ladder, point compression, point decompression, and others.

An advantage of using an elliptic curve in Montgomery form is that Montgomery ladder can be used for scalar point multiplication.

Algorithm 1 Montgomery Ladder.
INPUT: scalar n, point P
OUTPUT: nP

1. $R_0 \leftarrow O$
2. $R_1 \leftarrow P$
3. for $i \leftarrow m$ down to 0
4. if $d_i = 0$
5. $R_1 \leftarrow R_0 + R_1$ (*Point Addition*)
6. $R_0 \leftarrow 2R_0$ (*Point Doubling*)
7. else
8. $R_0 \leftarrow R_0 + R_1$ (*Point Addition*)
9. $R_1 \leftarrow 2R_1$ (*Point Doubling*)

10. end if

11. end for

12. return(R_0)

Now, we can talk about point compression and point decompression in Curve25519. The algorithm for point compression is straightforward from the existence of two points with the same x-coordinate on an elliptic curve, but with a different y-coordinate, i.e., point (x,y) and point $(x,-y)$, which is equal to point $(x,p-y)$. Because p is odd prime, if y is an odd number, then $p-y$ is an even number and vice versa. Hence, we can compress point (x,y) by $(x, y \bmod 2)$, of which the possible result is $(x,0)$ or $(x,1)$.

Remember that in Curve25519 the y-coordinate is defined when y is not a quadratic residue or $(x,y\sqrt{2})$. By the same argument, if $(x,y\sqrt{2})$ is on E, then $(x-(p-y)\sqrt{2})$ is also on E. However, before we can compress a point with form $(x,y\sqrt{2})$, we have to divide the y-coordinate with $\sqrt{2}$ to avoid problems in real computation. Then, the possible result when we compress the point with form $(x,y\sqrt{2})$ is also $(x,0)$ or $(x, 1)$.

Algorithm 2. Point Compression
INPUT: Point(x,y).
OUTPUT: Point(x,i)

1. if y quadratic residue modulo p then

2. $i \leftarrow y$ mod 2

3. return (x,i)

4. else

5. $y \leftarrow y/\sqrt{2}$.

6. $i \leftarrow y$ mod 2

7. return (x,i)

8. end if

The inverse algorithm for point compression is point decompression, i.e., recalling the "real" y-coordinate from point compression.

Algorithm 3. Point Decompression.
INPUT Point (x,i).
OUTPUT Point (x,y)

1. $z \leftarrow x^3+486662x^2+x$

2. if z quadratic residue modulo p then

3. $y \leftarrow \sqrt{z} \bmod p$

4. if $y = i \bmod 2$ then

5. return (x,y)

6. else

7. return$(x,p\text{-}y)$

8. end

9. else

10. $z \leftarrow z/2$ mod p

11. $y \leftarrow \sqrt{z}$ mod p

12. if $y = i$ mod 2 then

13. return $(x,y\sqrt{2})$

14. else

15. return$(x,(p\text{-}y)\sqrt{2})$

16. end

17. end

The next algorithms are used to recover the y-coordinate in elliptic curve Montgomery form, because we need it in ECIES.

Now we can give the algorithms for encryption and decryption. For a point generator P in Curve25519 that has a prime order n, if Alice sends message x to Bob with private key m so Q = mP, then Alice encrypts the message with the following algorithm:

Algorithm 4. Encryption in Simplified ECIES
INPUT: Plaintext a
OUPUT: Ciphertext $(V(x_1,y_1),c)$

1. $k \leftarrow$random$([1,n\text{-}1])$

2. $R(x_1,z_1) \leftarrow (k\text{-}1)P$

3. $Q(x_2,z_2) \leftarrow R(x_1,y_1)+P$

4. $R(y_1) \leftarrow Recovery\text{-}Y(P,R(x_1,z_1),Q(x_2,z_2))$

5. $U(x_3,y_3) \leftarrow R+P$

6. $V(x_3,y_3) \leftarrow$Point-Compression$(U(x_3,y_3))$

7. $V(x_4,y_4) \leftarrow kQ$

8. $y \leftarrow x_0.a$

9. return$(V(x_3,y_3),y)$

Note that in the above algorithm in line 4, there is the command “Recovery-Y.” This command is based on Okeya and Sakurai [7].

If Bob wants to read the actual message from Alice, then Bob decrypts Alice's message using the following algorithm:

Algorithm 5. Decryption in Simplified ECIES.

INPUT: Ciphertext$(y1,y2)$

OUTPUT: Plaintext a

1. $(x_0,y_0) \leftarrow mPoint\text{-}Decompress(y1)$

2. $a \leftarrow x_0^{-1}$

3. $b \leftarrow y_2 a$

4. *return b*

Since this elliptic curve contains a cyclic subgroup of prime order, it is possible to apply S-ECIES. For example, fix base point $P(X{:}Y{:}Z)$ with $X = 9$, $Z = 1$ (because in Curve25519, z_1 always has a value of 1), and the y-coordinate can be chosen randomly between odd and even integers that satisfy $y^2 = x^3 + 486662x^2 + x$. The chosen base point P has prime point order, with point order $m = 2^{252} + 2774231\ 777737235353585\ 937790883648493$. Hence, the curve can be implemented in S-ECIES.

Then, we choose a random integer, k, between 1 and m-1. Then, scalar multiplication of k with point $x = 9$ by using the Montgomery ladder algorithm produces $kP(X_k{::}Z_k)$, and by using a y-coordinate recovery algorithm we can get $kP(X_k{:}Y_k{:}Z_k)$. After that, we convert the projective coordinates to affine coordinates to get $kP(X_k/Z_k, Y_k/Z_k)$, and we use $Point\text{-}Compress(kP)$. Then the y-coordinate of ciphertext is the multiplication of plaintext x with x_3, where we get x_3 from $kQ = (x_3,y_3)$. Since we only use the x-coordinate of kQ, we can use Montgomery ladder with scalar k and point $Q = nP$.

For decryption, we first decompress $V(x_1,y_1)$ and then use private key n to get scalar multiplication nV, using only the Montgomery ladder algorithm. The last step is multiplying the y-coordinate of ciphertext with the inverse of the x-coordinate of nV to get the plaintext x. This inverse exists, because we are working in a prime field and the x-coordinate of V is not zero.

Now, we discuss arithmetic in F_p with $p = 2^{255}–19$. There are two operations in F_p, addition and multiplication. However, in F_p with $p = 2^{255}–19$, it is not that easy. Bernstein [1] used radix $2^{25.5}$, which is a polynomial with form $\sum \alpha_i x_i$ with i is a number between 0 and 9 and α_i is a multiple of $2^{[25.5i]}$ (where $[x]$ is the smallest integer that is larger than x) and $\alpha_i/2^{[25.5i]}$ is an integer between -2^{25} and 2^{25}. With the restriction that if i is an odd number then $\alpha_i/2^{[25.5i]}$ is between -2^{24} and 2^{24}, while if i is an even number then $\alpha_i/2^{[25.5i]}$ is between -2^{25} and 2^{25}, therefore, every element in F_p with $p = 2^{255}–19$ can be converted in radix polynomial form. The following algorithm converts integers to radix as follows:

Algorithm 6. Integers to radix $2^{25.5}$

INPUT: n

OUTPUT: $R(x)$

1. $d \leftarrow$ BINARY(n)

2. $p \leftarrow$ LENGTH(d)

3. $a \leftarrow 0$

4. while $p > 26$ do

5. if $a = 0 \ mod \ 2$ then
6. $p \leftarrow p\text{-}26$
7. $k_a \leftarrow 26$
8. else
9. $p \leftarrow p\text{-}25$
10. $k_a \leftarrow 25$
11. end
12. $a \leftarrow a+1$
13. end
14. $sum \leftarrow ZEROS(1,a)$
15. $k_a \leftarrow p\text{-}1$
16. for $i \leftarrow 1 \ to \ p$ do
17. if $d(i)=1$ then
18. $sum(a) \leftarrow sum(a)+2^{ka}$
19. end
20. end
21. for $i \leftarrow a\text{-}1$ downto 0 do
22. $l \leftarrow k_i\text{-}1$
23. for $j \leftarrow p+1$ to $p+k_i$ do
24. if $d(j)=1$ then
25. $sum(i) \leftarrow sum(i)+2^l$
26. end
27. $l \leftarrow l\text{-}1$
28. end
29. $p \leftarrow p+ki$
30. end
31. $g(x) \leftarrow (sum(0)+\ldots+sum(a)x^a)$
32. Return $g(x)$

From the above algorithm, first convert the integer to binary representation, and then from the right partition every 26,25,26,25,...,k, with $0 \leq k \leq 25$, as an example of an integer with length of binary representation is 231, then partition from the right 26,25,26,25,26,25,26,25,26,1. Every partition states the value sum of $d(i)2^{i-1}$, with d(i) is the value of the order of the binary representation that is either 0 or 1. Also, the j-th partition is the coefficient of x^{j-1}.

Example: Suppose we have a 15-digit number, 325606250916557, which has binary representation "1001010000010001100 01110 01110 11000 01010 10110 01101." For integers, 325606250916557 has two partitions, i.e., 00111011000010101011001101 and 1001010000010001100011 1. Therefore, the coefficient of x0 is $0.2^{25} + 0.2^{24} + 1.2^{23} + \ldots + 0.2^{1} + 1.2^{0}$, which if we calculated would be the value 15477453. In the same way, coefficient x1 would be the value 4851911. Thus, the number 325606250916557 represented by radix $2^{25.5}$ would be 4851911x + 15477453. Also, we can use.

addition and multiplication in radix $2^{25.5}$.

After we have converted any integer, there is an additional problem when the coefficient of radix $2^{25.5}$ exceeds our definition. For this problem, Bernstein [1] has already provided a solution.

5. Applications

Communication systems in the future are expected to interact between diverse types of devices. This allows the user to construct a personal distributed environment using a combination of different communication technologies. The security of transmitted data between these devices is a very important aspect.

Nowadays instant messaging is popular for personal and business communications instead of short messages (SMS) on mobile devices. However, most mobile messaging applications do not protect confidentiality or message integrity. Supervision over private communications conducted by the NSA motivates many people to use alternative messaging solutions for security and privacy of communication on the Internet. A messaging app that claims to be secure instant messaging and has attracted a lot of attention is TextSecure.

Elliptic curve cryptosystem (ECC) is a public-key cryptography suitable for use in environments with limited resources such as mobile devices and smart cards. In cryptography, Curve25519 is an elliptic curve that offers 128 security bits and is designed for use in the Elliptic Curve Diffie-Hellman (ECDH) key agreement key design scheme. This curve is one of the fastest ECC curves and more resistant to the weak number random generator.

In the TextSecure application, Curve25519 is used for key exchanges and authentication. However, in this paper we show that Curve25519 can also be implemented in simplified Elliptic Curve Integrated Encryption Scheme (S-ECIES). Therefore Curve25519 serves for key exchange, authentication, encryption, and decryption. As Curve25519 is built in such a way as to avoid potential attacks on implementation and avoid side channel attacks and random number generator issues, one may expect more secure communication systems.

6. Conclusion

The curve being used in this paper is $y^2 = x^3 + 48666x^2 + x$, a Montgomery curve, over the prime field $2^{255}–19$. This protocol uses elliptic point compression (only the X-abscissa), allowing for efficient use of Montgomery ladder for ECDH, which uses only XZ coordinates.

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In this research we develop efficient algorithms for elliptic curve cryptography using Curve25519 which is implemented in security of instant messaging.

Several algorithms have been established for the implementation of Curve25519 in simplified ECIES: Montgomery ladder for scalar point multiplication, point compression and point decompression, encryption and decryption in simplified ECIES, and the algorithm integer to radix for the arithmetic in F_p with $p = 2^{255}-19$.

In a future research, implementation of Curve25519 in Elliptic Curve Digital Signature Algorithm may be attempted.

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Section 4

Theorising Engineering Education

Chapter 14

Programme Integrating Courses Making Engineering Students Reflect

Viggo Kann

Abstract

A programme integrating course (PIC) is a special type of course, lasting for several academic years and aiming to strengthen programme coherence, by tying the students, instructors and programme director closer together. The first PIC was started at KTH in 2008. Since then, the concept has been polished and adopted by many engineering and masters of science programmes at KTH and at other universities. The course is built around regular (four times a year) reflection seminars in small cross-grade groups, mentored by a teacher. Each seminar has a topic, for example, study skills, procrastination, exchange studies, generic skills, minorities and equal treatment and ergonomics and mental health. Before the seminar, the students are presented with some material to read and view. Based on the texts and videos, each student should write a reflection document and read and comment some other students' reflections. At the seminar, the students will further discuss the topic and discuss the courses that they are currently taking. PIC has been evaluated and found very valuable by both the students and the teachers acting as mentors. This chapter will review the existing literature on PICs, which is mostly in Swedish.

Keywords: programme integrating course, self-regulated learning, programme coherence, reflection, engineering education

1. Introduction

1.1 Programme coherence and the programme triangle

A vocational education, such as engineering education and teacher education, can suffer from fragmentation [1–3]. Based on interviews with 20 graduated engineers, Nilsson found that the engineers 'view their education as compartmentalized or fragmented, and they lack a main thread in the educational programme' [3]. It may even be the traditional organisation of education that causes this [4]. The gap between theory and practice in education is argued to stem from a situation where, according to Schön, 'the privileged knowledge held in the research university is broken up into territorial units. Each field of subject matter is the province of a department, and within each department, knowledge is further subdivided into courses, the provinces of individual professors' [5]. Teachers/faculty from all departments involved in a study programme will need to cooperate [6], together creating, as Guardini put it, a 'living image of what it means to be a teacher, a man of law, or an engineer' [7, 8]. Jessop et al. [4] proposed 'Taking a programme approach clarifies the interconnectedness of units of study, emphasizing that an undergraduate degree is subject to a curriculum design process where the "whole is greater than the sum of its parts".'

Within professional education, the concept of *programme coherence* has emerged as a way of understanding and counteracting a fragmented education [9] and to 'bring into focus the complexity of the meaningful interrelationships between theory and practice' [10]. Tatto's starting point of programme coherence still holds as a definition for many subsequent professional educational researchers, stated as 'shared understandings among faculty and in the manner in which opportunities to learn have been arranged (organizationally, logistically) to achieve a common goal' [11].

The Swedish Higher Education Ordinance states that all first and second cycle education should be carried out in the form of courses. Courses form the concrete level in education. It is within the courses the teaching and learning should take place. The two *key actors* in courses are *instructors* and *students*. The courses may be organised into education programmes, and each course should have a course syllabus and each programme a programme syllabus. There should be intended learning outcomes stated for each course and education programme. The Higher Education Ordinance specifies qualitative targets, in compliance with the European Dublin descriptors, for each higher education qualification. The programme syllabus and qualitative targets, together with the learning outcomes of the courses included in the programme, form a formal/written specification of the education. For each education programme, there is often a *programme director* (or a group with the same authority), who is responsible for the abstract specification. This is the third *key actor* in our model.

The formal curriculum may be superficial or quite detailed. Over 100 engineering institutions follow the CDIO initiative, which emphasises the programme perspective [12], with a 'curriculum organized around mutually supporting courses,' represented by a matrix defining the progression of different skills through the courses in the programme. However, as we described above, there is a gap between theory and practice in education that has to be handled.

In the typology of curriculum representations by van den Akker [13], the *intended curriculum* includes both the ideal curriculum (the vision or basic underlying philosophy) and formal/written curriculum, the *implemented curriculum* is the operational curriculum perceived by the instructors, and the *attained curriculum* is the experiential learning of the students.

According to *variation theory*, the object of learning, or what the students need to learn to achieve the desired learning objectives, involves three parts: The *intended*

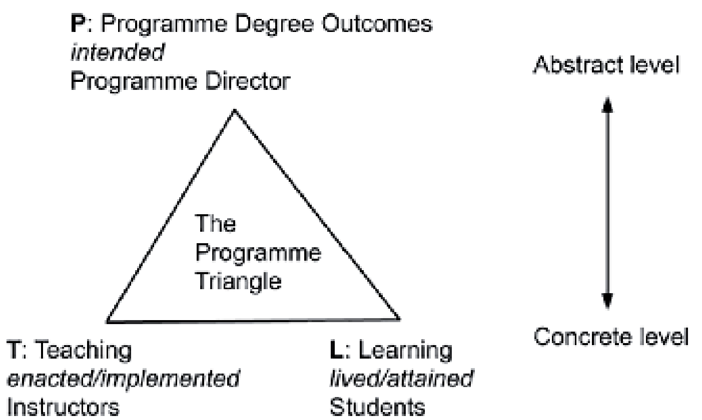

Figure 1.
The programme triangle.

object of learning will be the starting point for a lesson, course or unit. The *enacted object of learning* is the actual possibilities for learning that are provided. The actual learning that takes place in each individual student is referred to as the *lived object of learning* [14]. This corresponds nicely to the intended, implemented and attained curriculum, respectively, from van den Akker's typology, and is used in our new model, called the *programme triangle* (see **Figure 1**).

The programme director tries to influence the instructors and students so that the concrete courses (implemented curriculum) will comply with the programme director's abstract picture of the programme (intended curriculum).

In a *coherent programme* we suspect that the intended curriculum, the implemented curriculum and the attained curriculum are the same or close to the same. The coherence can be improved by making the six relations between the three key actors stronger, i.e. strengthening the edges of the programme triangle.

There are different processes, courses and structures that can be used to strengthen programme coherence. Examples of such activities, and which edges in the programme triangle they are meant to strengthen, are:

- A study skills and study strategies module (strengthening the L ← T relation)
- Student representatives and meetings (T ← L relation)
- Meetings of instructors (strengthening P ← T and T ← P relations)
- Information meetings for the students (L ← P and possibly P ← L relations)
- Course and programme questionnaires, graduate and alumni surveys (T ← L and P ← L relations)
- Academic introduction activities (L ← P and L ← T relations)
- Programme integrating courses (strengthening all six relations)

In this chapter, we will focus on programme integrating courses and show how they strengthen the programme coherence.

1.2 Self-regulated learning

Self-regulated learning refers to the degree to which individuals can regulate aspects of their thinking, motivation and behaviour during the learning process [15]. It is learning that is guided by *metacognition* (thinking about one's thinking), *strategic action* (planning, monitoring and evaluating personal progress against a standard) and *motivation to learn*. Therefore, self-regulated learning would strengthen the L ← P and L ← T relations in the triangle. There are several studies showing the importance of self-regulated learning for academic achievement, e.g. [16, 17]. Zimmerman [18] states that self-regulated learners use systematic and controllable strategies and concern their responsibility for achieving the learning outcomes. Students who are aware of the long-term goal of their programme, why they are taking the courses that they are taking and how they should study optimally, should be better prepared for their studies.

Another self-regulated process is *reflective practice*, which is the capacity to reflect on action to engage in a process of continuous learning. Schön [5] was one of the founders of this field. Reflective practice contains strategies for teachers to handle the T ← P and T ← L relations in the programme triangle.

1. Technical writing just describing personal experience, events and action in a specific situation
2. Descriptive reflection analysing one's performance, giving reasons for actions taken
3. Dialogic reflection considering alternatives exploring alternative viewpoints and alternative ways to solve problems
4. Critical reflection from a broader perspective thinking about the effects upon others of one's actions, taking society into account

Table 1.
Hierarchy of reflection levels.

1.3 Reflection and levels of reflection

In the programme integrating courses, reflection assignments, orally and in writing, are heavily used as a tool to both strengthen the programme coherence and promote self-regulated learning among the students.

The students are regularly given reflection assignments on different topics, related to Zimmerman's learning strategies mentioned above [18]. The students get feedback on their reflections in several ways: written peer feedback, written feedback from the mentor and feedback in the oral discussions at the seminar. Feedback is important to facilitate self-regulation [19].

We soon noticed that we would need to encourage the students to write deeper reflections. It is known that students may experience difficulties when being asked to reflect on a given topic, which can lead to more descriptive than reflective texts [20, 21]. In order to help students to improve their ability to reflect more deeply, Kann and Magnell developed a model, summarised in **Table 1** [22], based on research by Hatton and Smith [21]. In Section 4.4 we will explain how these levels can be useful in order to support our students to create sophisticated reflections and to use their reflections to improve self-regulated learning.

2. Programme integrating courses

The first *programme integrating course,* of the type considered in this chapter, was developed by Björn Hedin and given in 2008, for engineering students in Media Technology at KTH [23]. This course will be denoted PIC1 below. In 2010, a course based on PIC1 was introduced for Computer Science and Engineering students at KTH (denoted PIC2). These courses have the same structure and differ only in some details. We have chosen PIC2 as the reference course in this chapter.

The programme integrating course is not at all an ordinary engineering course; it can be characterised as a meta-course. The intended learning outcomes and aims of the course are presented in **Table 2**.

A Swedish master of science in engineering education takes 5 years. At KTH, the first 3 years (first cycle) of each engineering programme consist mostly of mandatory courses. In year 3, the student chooses a master's specialisation for the last 2 years of their education (second cycle). These master's specialisations are also possible to take as separate master's programmes for external students. The success of PIC1 and PIC2 made us realise the need for a programme integrating course also in the master's programmes. We were even approached by students who had taken PIC2, expressing interest in a continuation of the PIC. In this chapter, we will use the PIC in the Master of Science in Computer Science as the example of such a course. We will denote it PIC3.

The students in each programme integrating course are divided into seminar groups. Each group consists of students from different years of the programme and one mentor, a teacher on the programme. The course is centred around four reflection

Having passed the course, the student should be able to:

- Use academic calendars, course syllabuses, intended learning outcomes and grading criteria to plan their studies in both the short and the long view
- Plan and carry out assignments in stipulated time
- Make well justified specialisation and course choices
- Review critically and reflect on both the setup and implementation of the education as well as their own study achievements
- Reflect on different topics relevant for the education and the professional role, such as progression in subject knowledge and generic skills, plagiarism, own responsibility, study technique, procrastination, internationalisation, health, minorities and equality, student influence and quality of education
- Identify their need for additional knowledge and continuously develop their competence
- Analyse and evaluate social and ethical consequences of computer applications

In order to:

- Obtain an overall picture of the education and thereby better understanding of the importance of each individual course
- Make informed choices both during the education and thereafter
- Influence the development of the programme

Table 2.
Intended learning outcomes and aims of the course.

Course	PIC1	PIC2	PIC3
Number of years	3	3	2
Cycle	First	First	Second
Part of education programme	Media Technology	Computer Science and Engineering	Computer Science
Year first given	2008	2010	2014
Number of groups	20	39	24
Number of mentors	6	13	12
Number of students per group	10–12	12–14	16–18
Length of seminar	80 minutes	60–70 minutes	50 minutes
Grading of seminar activity	Yes, point system	Yes, two levels	No, pass/fail
Grading of reflection documents	Yes, point system	Yes, two levels	No, pass/fail
Peer comments	Yes, within the group	Yes, from 2018	Yes, within the group

Table 3.
Data about the three instances of PIC discussed in this chapter.

seminars each year, each with a dedicated topic, such as procrastination or ethics. Before each seminar, the students are asked to study the topic and write a reflection based on their own experiences. The four-level reflection hierarchy in **Table 1** has been used in PIC1 and PIC2 for several years now. At each seminar, the students also reflect upon recently taken courses. The reflection is shared to the group members including the mentor, who asynchronously discuss the texts online (using either Google Documents or the Peergrade.io system). The topic and the courses are then discussed further at a physical meeting, sometimes in the form of a walking seminar [24], where the group discusses the topic while walking in the woods behind campus.

In different PICs the students' reflections and participation are assessed in different ways and using different grading scales (see **Table 3**).

3. Characteristics and functions of the course

In this section, we will describe the programme integrating course through its characteristic features and its functions in the education [22, 25].

3.1 Characteristics of PIC

The first function of the programme integrating course, as we will see in the next subsection, is academic introduction. Andersson et al. [26] have identified five key concepts that characterise successful activities for academic integration and improved student completion. We will show that the programme integrating course is characterised by all these key concepts, by going through the five concepts and explaining how PIC2 is characterised by them.

3.1.1 An overall perspective

PIC runs for the whole first 3 years of the education and is mandatory for all students. All categories of staff who are directly involved in the programme are involved in PIC: the programme director, the study counsellor and 13 instructors who are teaching courses in the programme.

Furthermore, PIC ties together the mandatory courses of the programme and guides the students in their choices of elective courses and specialisations. It covers most aspects of the studies: objectives, execution and development of the courses, study skills and personal health, profession and lifelong learning.

3.1.2 Student activity

Four times each year, the students meet in small cross-grade groups. Each student has the same group and the same mentor each time. Before each seminar each student should write a reflection document, read the reflections of the other members of the same group and comment on them. During the seminar, the written reflections are discussed, usually first in small groups and then in the whole group. PIC is permeated by student activity.

3.1.3 Personal meetings

The seminar groups consist of about a dozen students from different years (1–3). In the yearly evaluation, many students emphasise that the meetings with students in other years are especially fruitful. Since the students meet the same instructor as mentor during all 3 years, a mutual trust is developed. At the end of the third year, the mentor meets each student individually for 15 minutes and discusses the important choice of master programme and specialisation. The students also meet the study counsellor once or twice a year within the course.

3.1.4 Forward-pointing

Our aim is that the course participants should become skilled and conscious self-regulating students, aware of the objectives of their education programme, why the courses in the programme are included in the education and how they build on each

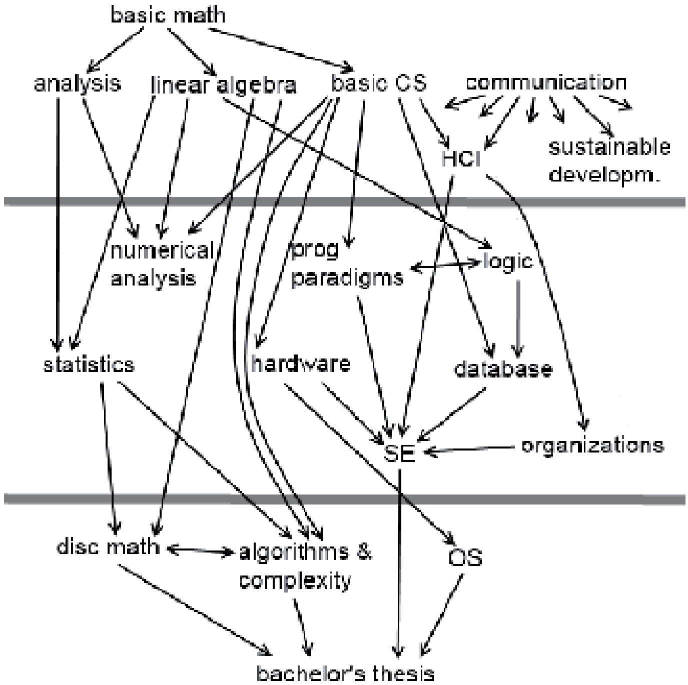

Figure 2.
A graph showing how the mandatory courses of the programme are linked to each other. This picture is shown and discussed at all lectures of PIC2, i.e. twice a year.

other. Furthermore, the students should be able to make informed choices to get the vocational training and education that they seek. The discussions about current courses, in the second half of each seminar, show younger students what they will meet in their education in 1 or 2 years.

3.1.5 Discourse awareness

The very first lecture in the first year of the programme is a PIC lecture, where we show the students how the mandatory courses of the programme are linked (see **Figure 2**), how the programme is run and developed, which course administrative systems exist and where to find answers to questions and get help—knowledge that will simplify life as a student. The textbook used gives further insight into the academic discourse.

Each PIC seminar has a topic that raises the consciousness about some academic discourse, which makes the students aware of many discourses spread out over the 3 years that the course is given. The topics are shown in **Table 4**, in order of popularity according to a survey answered by all third-year students 2019. The topics rotate in a 3-year cycle.

We have shown that PIC meets all five key concepts. Hence, it is likely that PIC is a successful activity for academic integration and improved student completion.

3.2 Functions of PIC

The programme integrating course is a multipurpose course. Kann [25] argues that PIC fulfils the following 10 functions:

1. Academic introduction (strengthening L ← P and L ← T relations)

52%	Ergonomics and mental health
46%	Master programmes
40%	Procrastination
34%	Minorities and equal treatment
30%	Study motivation and study skills
30%	Professional life as a CS engineer and lifelong learning
25%	Quality in the education—what is that?
23%	Studying and working abroad
11%	Plagiarism and responsibility
8%	Learning outcomes, criteria and assessment

Table 4.
Results of the evaluation question: 'Which three seminar topics do you think were most fruitful?'

2. Increased understanding of the programme (L ← P relation)

3. Connections between teachers and students (T ← L and L ← T relations)

4. Exchange of experiences between students from different years of the programme (L ← L, L ← P and L ← T relations)

5. Training in written and oral communication and reflection (curriculum)

6. Information about elective courses and studies abroad (L ← P relation)

7. Follow-up of academic results (T ← L relation)

8. Covering subjects that other courses are not covering (curriculum)

9. Education of the instructors involved (T ← P and T ← L relations)

10. Quality enhancing evaluation of the programme (all L ⇄ T ⇄ P relations)

The motivation of function 1–7 should be clear from the above characterisation. Let us motivate the last three functions.

There may be important but small subjects that are parts of the overall objectives of the programme but are not included in any ordinary course. This was the case for us for ethics, plagiarism, computer science history and the computer in the societal development. Therefore, we extended PIC with an ethics module and a computer history model and added plagiarism as a seminar topic. This is an example of the eighth function of PIC.

Function 9 concerns the education of the instructors who are acting as mentors, which is of two kinds: First, PIC gives knowledge about the programme, its objectives, contents and courses to the students, but the mentors need to read the preparation material before each seminar, so they will get the same knowledge. Second, the mentors will learn, by reading reflections and listening to the discussions at the seminars, how the students experience their studies and how they study and prioritise. The mentors can then use this knowledge to improve their own courses and make them more suited to the programme.

Regarding function 10, there are several common problems with ordinary course evaluations that PIC solves. Many course surveys have low participation, but in PIC the surveys are mandatory. This is possible because the fourth intended learning outcome of the course is 'review critically and reflect on both the setup and implementation of the education as well as their own study achievements' (**Table 2**). Another feature of the surveys in PIC is that questions can have a programme perspective, which is not possible or at least not that easy in a survey in a singular course.

Last, but not the least, the course reflections at the end of each seminar give direct feedback on the ongoing courses, independently of which department they belong to. The mentor collects the feedback and presents it to the other mentors (including the programme director) at a short meeting over a cup of coffee the day after the seminars. This allows for acting on the feedback swiftly.

4. Analysis of the effects of the programme integrating courses

The effects of programme integrating courses have been analysed in a sequence of publications, several of them only published in Swedish [22, 25, 27–30]. In this section, the results of these publications will be summarised.

4.1 Methods of evaluation

Six different methods for collecting data have been used in the evaluations:

- *Mandatory surveys*: at the end of each academic year, all PIC2 and PIC3 students should answer a mandatory survey. This is one of the ways that the students show fulfilment of the fourth of the intended learning outcomes in **Table 2**, as explained in Section 3.2. These surveys are used both to evaluate the course itself and the programme, but they can also be used for other purposes, as shown in Section 5. Many questions have been the same for several years, so it is possible to compare answers to the same questions from both different years of students and different years of the survey. At some seminars, we have given the students surveys of specific topics, such as study skills (see Section 4.3), procrastination or learning strategies (see Section 5.4). We always make a summary of the results available to the students, often as a basis for reflection and discussion.

- *Interviews with students*: students, 22 in total, of different PIC courses (PIC1, PIC2 and PIC3) and years have been interviewed by the doctoral student Emma Riese in 2018. The questions were mainly about the experience of PIC. The interviews have been transcribed and analysed.

- *Interviews with mentors*: six teachers working as mentors in different PIC courses have also been interviewed by Emma Riese, mainly about experiences of PIC. The interviews have been transcribed and analysed.

- *Survey to mentors*: a survey was sent to all mentors of PIC1, PIC2 and PIC3 in 2018. Of 25 mentors, 22 did answer the survey.

- *Document analysis*: the PIC2 reflection documents handed in by the students 2010–2016, many thousands of documents, have been automatically analysed by a language technology-based system, in order to study the progression of reflective ability and the language quality (see Sections 4.4 and 5.2).

- *Number of students studying abroad*: in order to study the influence of the seminar on the topic *studying and working abroad*, we have collected the numbers of exchange students during 5 consecutive years (see Section 4.5).

4.2 Experiences of the course

How do the students and mentors experience the programme integrating courses? Some results from the mandatory survey of PIC2 at the end of the academic year 2018/2019 are shown in **Table 5**. In each of these five questions, the students should answer on a Likert scale from 1 to 7 whether they agree or not to a statement. In the scale, 1 means *totally disagree* and 7 means *fully agree*. The same questions have been asked for a sequence of years, and the results are almost stable.

We can see that already from year 1, the students understand the aims of the seminars. They also, throughout the 3 years, appreciate listening to elder or younger students. The interviewed students confirmed this and even expressed that sharing an experience that could evoke change was the main benefit of the course.

The students value the programme integrating course more and more during the course of the course. At the end of the course, a majority of the students rank the fruitfulness of the course to 6 or 7 on the Likert scale. Increase of the knowledge of the education through PIC is also something that students rank higher in the third year than in the first year.

The student interviews showed that discussing the courses of the programme and how they link to each other was considered to be an important part of PIC, where the mentors were seen as gateways to change things. Some interviewed students considered some seminar topics to be nontechnical and far from what they chose to study and therefore not that valuable. The interviewed mentors confirmed that a few students' attitudes towards some topics were disappointing. Some mentors expressed that discussing these topics could be out of their own comfort zone. The proportion of students answering below 4 (i.e. were negative) to the fruitfulness of the 8 first seminars of the course varied between 8% (master programmes topic) and 28% (learning objectives, criteria and assessment topic).

Some of the interviewed students expressed that timing of the reflection assignments always was the worst possible—when all parallel courses had assignments due. One should note that the students get the assignment about 10 days before the deadline and that the assignment will take about 3 hours to complete.

Experienced mentors expressed that they were fortunate to be able to follow the development of their students throughout the 2 or 3 years of the course, to be able to learn their names, which is often not possible in the ordinary courses where the number of students is often over 200.

	Year 1	**Year 2**	**Year 3**
I understand the aims of the seminars and activities of the programme integrating course	5.8	5.9	6.1
I feel that I am better at writing reflections now than when I started the programme	3.8	4.4	5.2
It has been interesting and rewarding to listen to students from other years at the seminars	5.9	5.9	6.0
My knowledge of the education has increased considerably through PIC	4.4	4.8	5.4
Overall, the programme integrating course has been fruitful	4.8	5.0	5.6

Table 5.
Results from the survey 2019. The students were asked how well they agree with a set of statements on a Likert scale from 1 (I totally disagree) to 7 (I fully agree). The mean values of the answers are shown in the table.

The students often described a good relationship with the mentor, a relationship of trust. However, not all mentors seem to be engaged to the same extent in the course.

Many more experiences of PIC are reported in [28, 29].

4.3 Improving study skills

Hedin and Kann [30] have studied the effects of the programme integrating course PIC2 with respect to study skills. The course starts with a learning-to-learn module, consisting of the following parts:

1. The students are instructed to look at least four of nine short videos, where Björn Liljeqvist, a young specialist in study skills, explains and motivates the use of a number of study skills. They are also instructed to read a short book on how to study.

2. The students write a reflective text about their own study habits and choose at least one new study skill to try for the next months.

3. The students read each other's texts within the group.

4. The students in the group meet and discuss the topic and their reflections in a one-hour seminar.

5. About 6 weeks later, the students write a new text, reflecting on how the attempt to try a new study skill fell out, and discuss this at a new seminar.

The evaluation shows, among other things, which effects the students believed the study skills had after trying them (see **Table 6**). No significant change was found in how satisfied the students were with their overall study technique immediately after the initial module, but in the long-term, 77% of the students believed the course had promoted their ability to analyse and adapt their study habits [30]. The proportion of students who believe that PIC has promoted this is largely the same in different years and in different surveys.

4.4 Progression of reflection

We wanted the students to improve their ability to reflect more deeply. Therefore, we in 2012 developed and introduced a four-level model for reflections

What is your perception of the effects on your learning of	Obvious effect (%)	Most likely effect (%)	No noticed effect (%)
Preparing before lectures?	23	69	8
Taking smart notes at lectures?	23	57	21
Going through the previous day's and week's teaching?	23	63	15
Planning my studies the upcoming week?	49	40	11
Maintaining a study diary?	23	45	32
Reading the course literature in three steps?	44	37	19
Trying to stop procrastinating?	59	31	10
Doing some other change?	43	57	0
In total (mean values)	35	51	14

Table 6.
Results from the postquestionnaire on the effects on the students' learning.

(see **Table 1**) [22]. The reflection documents are graded in two passing grades, and from 2012 we required that the reflection should reach level 3 and 4 for students in years 2 and 3, in order to receive the highest grade. Since the students are reading each other's reflection documents, the first-year students could learn how to reflect more deeply when reading the reflections of the older students.

We developed a language technology-based system that is able to measure the depth of a reflection, according to the model in **Table 1** [28]. When comparing the mean reflection level of the reflection documents by the same students in the beginning of year 1 and in the end of year 3, we can see that the mean reflection level is raised from year 1 to year 3 for every student group and that the increase became larger after the introduction of the four-level model [28].

Thus, introducing the four-level reflection model and assessing the students' reflection documents using this model improved the mean progression of reflection from the beginning of the course to the end of the course.

The students are aware of this progression. When we ask them if they feel that they are better at writing reflections than when they started the programme, the students at the end of their first year do not see any clear improvement, but after year 2, and even more after year 3, the improvement is evident (see **Table 5**).

4.5 Inspiration for exchange studies

Before the seminar *studying and working abroad*, each student has to read about how exchange studies work and read three travel reports from students who have studied abroad. Then each student should reflect on exchange studies and discuss with the other students in the ordinary PIC way. Our hypothesis was that the introduction of this seminar should increase the number of students studying abroad. The number of students studying abroad almost doubled after the introduction of the seminar, which might indicate a correlation [28].

5. Usage of the course

Mandatory surveys in the course (see function 10 in Section 3.2) are an important and versatile tool. In this section, we will look at five examples of how submitted reflection documents and mandatory questions to all students in all years can be used.

5.1 Student-based programme development

In the mandatory questionnaire in PIC2 and PIC3 in 2016 (and again in 2019), we asked the following question: 'Give at least one proposal for how the master's programme in computer science and engineering could be improved.'

Almost 800 suggestions for improvements were received, at least one from every active student. We manually sorted and categorised the suggestions into 25 categories, with respect to what each suggestion aims to improve.

We then prioritised the suggestions: already implemented, should be implemented immediately or when possible, needs further work to become useful, save for future consideration or reject.

We selected 24 suggestions that would be possible to implement and presented them to two student representatives, who prioritised which suggestions we should proceed with in the next stage.

We proceeded with 14 suggestions. In a new mandatory questionnaire in PIC2 and PIC3, we now asked each student to evaluate each suggestion on a seven-point scale and, optionally, comment. Finally, we analysed the evaluation and started to implement the suggestions approved by the students into the programme.

We found that it is possible to collect suggestions for improvement and opinions on them from all students that most suggestions were realistic and well founded.

Furthermore, we could see what support and what opposition each suggestion would meet if implemented. For each suggestion, we got comments showing possible positive effects or obstacles that we did not think of ourselves.

This approach, which we call *student-based programme development*, thus gives us a very good foundation for deciding whether and when the suggestions should be implemented [31].

5.2 Studying language quality

In Sweden, there has since 2013 been a debate in public media, where university professors, mostly from departments of history, have argued that today's students entering university are much less accomplished than earlier students when it comes to basic Swedish language skills. According to the debate, both the spelling and grammar of Swedish students are weak. The first signs of these are said to have been observed in 2010. In order to objectively study the language skills of Swedish first-year university students, we constructed an automatic tool, based on language technology, which measures the language skills that, according to the critics, have been deteriorating. We used the tool on the PIC2 reflection documents from the first seminar from seven different years, 2010–2016. The results show, surprisingly, that the language skills of the studied groups of students have not deteriorated during the period. If anything, the skills have slightly improved regarding the level of complexity of the language [32].

5.3 Studying competencies

The next example is an effort to find out which competencies the students had attained through studying the programme ('attained competencies') and compare these to the competencies that the programme director has stated that the programme should result in ('intended competencies').

In the mandatory questionnaire, we asked the students 'Which competencies do you think are the most important that you have developed/will develop during your studies at KTH?'

From the answers of the first-year students and fourth-year students, we built two separate sets of competencies, by clustering the student stated competencies and formulating aggregated competencies describing the simple competencies in each cluster.

When comparing the two sets to each other, we found no large differences. And when comparing the sets of competencies to the programme objectives defined by the programme director, they were unexpectedly similar. Thus, the students' collective view of the programme objectives seen as competencies was quite close to the programme director's view. This shows a good programme coherence with respect to the P $\rightleftarrows$ L edge in the programme triangle [33]. This is in contrast to Nilsson's interviewed engineers, who consider the educational and professional competence bases to be only loosely coupled [3].

5.4 Studying learning strategies

There are different tools for measuring learning strategies, such as deep, surface and strategic learning strategies. In mandatory surveys in PIC1 and PIC2, we have

How often do you feel stressed because of your studies?	Uppsala	KTH Computer Science and Engineering			
		Year 1	Year 2	Year 3	All
Never	1%	5%	4%	6%	5%
About every month	12%	30%	28%	19%	12%
About every week	32%	41%	40%	47%	43%
About every day	55%	24%	28%	29%	27%

Table 7.
Results from Uppsala University and KTH of a stress survey question.

used two such tools, ASSIST and RSPQ. The individual result was sent as feedback to each student, together with the summarised results of the whole group.

On group level, there are no large differences between the programmes or between the years of the students. However, there were quite large differences between the tools, especially for some individuals. Therefore, students testing their learning strategies by using one of these tools should not trust the results [34].

5.5 Studying stress and health

In the final example, Kann and Lundkvist [35] used the mandatory survey to replicate a study of the experience of stress among students, which had been performed at Uppsala University some months earlier. The same questions on stress were given to the PIC2 students from year 1–3:

- How often do you feel stressed because of your studies?
- If you feel stressed of your studies, what do you think are the reasons?
- To which degree do you estimate that stress is a problem/obstacle for you in your studies?

We compared the answers of the students from different years and to the Uppsala students (see **Table 7**). The most common reasons for stress among the PIC2 students were nervousness before the exams, high (own) performance demands and that leisure activities are prioritised before studies. For about half of the students, the stress is sometimes a problem.

The PIC2 students got the compiled results as a part of the reading to the seminar about *ergonomics and mental health*. This seminar was appreciated by the students—it was in fact the most popular seminar (see **Table 4**).

6. Discussion

The programme integrating course was given in 2008 for engineering students in Media Technology, and in 2010 the course was introduced for Computer Science and Engineering students. Thereafter the course has spread rapidly, both to other engineering programmes and to master's programmes. In 2013 it was adopted by two engineering programmes at Linköping University [36]. In 2019, there exist at least 20 successful implementations of the course in different programmes at KTH and Linköping University. The basic structure of all these courses is the same, but there have been local modifications, both in topics and in add-ons to the seminar and reflection part of the course.

There have also been a few unsuccessful attempts to start a programme integrating course, where the course has had to be removed, since it did not work. The reasons might be that the involved instructors did not believe in the course themselves and that the students got an initial bad impression of the course, which was difficult to change.

Many students express that the best part of the course is the sharing of experiences with other students, especially students from other years, at the seminars. Discussing the courses of the programme and how they link to each other was also considered to be an important part of PIC, where the mentors were seen as gateways to change things.

At a technical university, many students are sceptical to the elements of the education that they consider to be nonscientific or irrelevant to their future profession. The focus of the programme integrating course is on practicing soft skills, dispositions and attitudes, which makes it a target for such scepticism [29]. Therefore, we take care to show the direct or indirect benefit related to the engineering profession, for every topic that we introduce to the students. This is also in line with the course, since the programme objectives and the professional role are central parts of the course.

The surveys in the programme integrating course are mandatory. A high response rate is important for the quality of the results of the survey [37]. However, by forcing students to answer a survey, the quality of the answers might drop. Since the surveys are anonymous—the survey system is hiding information on who has answered what—students could write a nonsense answer to an open question without being held responsible for this. In our experience, this is not the case. It is extremely uncommon that answers are noticeably unserious. However, we do not know how often answers look serious but are untruthful. We try to make the students take the surveys seriously by asking relevant questions, by explaining the importance of the survey and by showing that former surveys have had an influence on the programme, the course itself or other courses.

From the perspective of the programme, the greatest benefit of the course is probably that it makes the student reflect regularly and with high quality, which will improve the self-regulated learning, identify problems in courses and the programme that can be swiftly handled, etc.

As shown above, the programme integrating course improves the programme coherence, which is important for a prosperous educational programme. However, Hammerness emphasises that coherence should not be viewed as an end product but rather a process 'as part of the steady work of such programs, a continuing and necessary effort of adjustment, revision and calibration' [2]. The programme integrating course has been shown to not just improve the programme coherence but also to have many other functions.

Further research should investigate the concept of programme coherence more deeply and study other ways of improving the programme coherence, besides programme integrating courses. Another area needing more research is the effect of different forms of reflection seminars, such as the full-group seminar, the split group seminar and the walking seminar [24]. The question why some attempts to introduce programme integrating courses fail while others (a clear majority) are successful would also be valuable to study in more detail.

7. Conclusions

In this chapter, we have explained how a *programme integrating course* can strengthen the six different relations involved in the programme triangle (**Figure 1**), between the students, the instructors and the programme director, in short improve the *programme coherence*.

In Section 3, we presented 10 important functions of the course, for example, academic introduction, increased understanding of the programme, connections between teachers and students, exchange of experiences between students from different years of the programme, education of the instructors involved and quality-enhancing evaluation of the programme.

We have seen that the students in general understand the aims and activities of the course, appreciate meeting and learning from students from other years at the seminars and overall think that the course is fruitful. As the course advances for three academic years, the students increase their knowledge about their education, improve their ability to reflect and improve their study skills. Their appreciation of the course grows for each year. We can see that the students develop in each of the three dimensions of self-regulated learning: metacognition, motivation and good habits. We have also seen that a topic at a single seminar can have a clear effect, since the number of students studying abroad almost doubled after the introduction of a seminar on studying and working abroad.

Finally, in Section 5 we showed that the course can also be used as a vehicle for student-based programme development and studies of different student related variables, such as language skills, learning strategies and stress.

A programme integrating course could be a valuable addition to any engineering education programme. The course takes very little space in the curriculum (the reflection seminar part of the course can fit in as little as 1 ECTS credit per year) and the gains from introducing the course can be substantial, especially for programmes where the programme coherence is weak or where the academic introduction is unsatisfactory. The topics of the seminars should be chosen to fit the current needs of the specific programme.

We suggest that every programme director of an engineering educational programme should seriously consider starting a programme integrating course, based on the general model described in this chapter and adapted to the local situation at the university and of the specific programme.

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