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Bridging the Future
STEM Education Across the Globe

Edited by Irene Govender
and Desmond Wesley Govender

Bridging the Future - STEM Education Across the Globe

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Aims and Scope of the Series

Education and Human Development is an interdisciplinary research area that aims to shed light on topics related to both learning and development. This Series is intended for researchers, practitioners, and students who are interested in understanding more about these fields and their applications.

Meet the Series Editor

Katherine Meltzoff received her BA in Psychology from Trinity College, in Connecticut, USA and her Ph.D. in Experimental Psychology from the University of California, San Diego. She completed her postdoctoral work at the Yale Child Study Center with Dr. James McPartland. Dr. Meltzoff' doctoral dissertation explored neural correlates of reward anticipation to social versus nonsocial stimuli in children with and without autism spectrum disorders (ASD). She has been a faculty member at the University of California, Riverside in the School of Education since 2016. Her research focuses on translational studies to explore the reward system in ASD, as well as how anxiety contributes to social challenges in ASD. She also investigates how behavioral interventions affect neural activity, behavior, and school performance in children with ASD. She is also involved in the diagnosis of children with ASD and is a licensed clinical psychologist in California. She is the Assistant Director of the SEARCH Center at UCR and is a faculty member in the Graduate Program in Neuroscience.

Meet the Volume Editors

Professor Irene Govender is a Professor of Information Systems and Technology at the University of KwaZulu-Natal, with over 25 years of experience in higher education, including 15 years in teacher education for computer science. She is an NRF-rated researcher with 80+ peer-reviewed publications and global citations. Her interests include Big Data Analytics and programming education. She has led and contributed to numerous educational and ICT projects, developed HEQSF-aligned curricula, and served as moderator, assessor, and external reviewer for various international institutions. A former mathematics teacher and chief IT examiner, she has also served as a reviewer for over 20 international journals and on NRF committees. She has engaged in global academic collaborations and thesis examinations, enriching IT/ICT and education across borders.

Professor Desmond Govender began his academic career as a mathematics and computer studies teacher for 13 years. Subsequently, he served as a Subject Advisor in Computer Studies for the KZN Department of Education. Prof. Desmond Govender joined the University of KwaZulu-Natal in 2000 and is presently the Discipline Leader in the Department of Computer Science Education in the School of Education. His research interests are ICT integration in teaching and learning. He is presently an NRF-rated researcher with over 60 publications. Prof. Govender is also responsible for quality assurance as the External Moderator for Umalusi for the FET subject Information Technology for both the Department of Basic Education (DBE) and the Independent Examinations Board (IEB).

Contents

Preface

STEM education, an interdisciplinary blend of science, technology, engineering, and mathematics, has become a major factor determining our future. With complex challenges such as climate change, digital transformation, and economic shifts, STEM education must evolve beyond technical proficiency. Hence, it must become a vehicle for empowerment, creativity, and social change.

This book, *Bridging the Future – STEM Education Across the Globe*, emerges from a growing recognition that STEM education must be inclusive, innovative, and internationally informed. We aim to present diverse perspectives, research findings, and practical insights from educators and scholars working across varied geographic, cultural, and economic contexts. In doing so, we seek to bridge gaps between regions, disciplines, educational systems, and generations of learners.

We, the editors, Prof. Irene Govender and Prof. Desmond W. Govender, bring together years of academic leadership, educational innovation, and collaborative research. As editors, we take pride in curating this collection that encapsulates the challenges and advancements encountered within the global STEM education community. This volume presents neither a singular model nor a definitive solution. Instead, it initiates a dialogue that transcends countries and fields regarding the preparation of learners not only for future employment but also for the responsibilities of global citizenship and ongoing inquiry.

The chapters featured in this book include:

Chapter 1, “Introductory chapter: STEM Education across the Globe”, gives a brief perspective of STEM education in general and its impact on the future.

Chapter 2, “Perspective Chapter: Mathematics for Teaching – It’s Not (Just) Pedagogy”, provides a reflective mathematics education perspective, challenging assumptions about pedagogy and content knowledge.

Chapter 3, “Enhancing Mathematics Education through Flipped Classroom Approaches: Insights and Best Practices”, discusses and presents practical strategies for flipped classroom instruction that enhance student agency and engagement in mathematics.

Chapter 4, “STEM Skills in the Development of Modelling Projects: The Stray Animal Growth Model”, presents an applied modelling project using stray animal population growth, merging social awareness with mathematical modelling and systems thinking.

Chapter 5, “Using Educational Robotics (ER) to Promote STEM Problem-Solving in Preservice Teachers”, gives a deep insight into Educational Robotics and how it equips preservice teachers with problem-solving tools grounded in active learning.

Chapter 6, “Perspective Chapter: Building a Multisector STEM Learning Ecosystem at the San Antonio Museum of Science and Technology”, documents a case study of building a multisector STEM learning ecosystem in San Antonio, highlighting the value of partnerships between education, industry, and cultural institutions.

Chapter 7, “Examining Access and Inclusion in STEM Fields in Higher Education: Digital Learning Environments, Personalized Learning, and Institutional Change to Advance Educational Opportunity”, critically examines access and inclusion in higher education, focusing on digital learning environments and personalized instruction.

These contributions span theoretical discourse and practical applications, authored by individuals who are not only experienced in their fields but also deeply committed to educational transformation.

We thank each contributing author for their scholarship, dedication, and forward-thinking inputs to this project. Their work forms the core of this volume, demonstrating the depth and diversity of STEM education today.

Finally, we extend our gratitude to the academic reviewers (reviewed by at least two independent reviewers, including the editors) and the support teams of IntechOpen publishing, who ensured that each chapter met the highest standards of clarity, rigor, and relevance.

As editors, we aim not to define a single future for STEM education but to illuminate the many pathways that lead toward equity, innovation, and global collaboration. We invite readers to engage with this book as both a resource and an inspiration for their journeys in STEM education.

Irene Govender and Desmond W. Govender
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Chapter 1

Introductory Chapter: STEM Education across the Globe

Irene Govender

1. Setting the scene

This introductory chapter provides a reflective perspective on the state of STEM education, inviting readers to explore its transformative potential while considering its successes and ongoing challenges. One is thus inclined to ask, What is STEM, and why is it important?

STEM combines Science, Technology, Engineering, and Mathematics into practical, problem-solving instruction rather than teaching these disciplines as separate subjects. Early efforts concentrated on using science and technology to address global competitiveness. More recently, stressing the value of comprehensive education, variants of STEM, including STEAM (which includes the Arts) and STREAM (which incorporates Research and Reading), have become popular. Including arts and research into the STEM ecosystem highlights the need for flexibility and creativity in education since it reflects the evolving needs of society and business. Seeing this development makes it abundantly evident that STEM education is a dynamic ecosystem interacting with every facet of societal advancement rather than only a set of courses. This integrated learning model helps students to acquire technical expertise, critical thinking, creativity, analytical techniques, communication skills, and cooperative problem-solving skills [1].

These skills are highly transferable and beneficial across many career paths, from healthcare to finance and even the arts. Hence, STEM education equips students with the tools to deal with complex problems, adjust to new technologies, and create original ideas in their particular fields. This adaptability improves their employability and helps them contribute actively to different sectors.

Thus, a dynamic, forward-looking approach to STEM education is more essential than ever in today's fast-changing environment [2]. Across a spectrum of cultural and economic landscapes, educators and practitioners are challenged to rethink conventional models, embrace innovative teaching methods, and explore cutting-edge technologies that resonate with the needs of contemporary society.

Interactive digital platforms, robotics kits, and immersive virtual simulations—which bring abstract scientific ideas to life and engage students in hands-on exploration—have become standard in many classrooms as technology is transforming learning environments. These advancements point to a fundamental shift from passive knowledge acquisition to active, experience-based learning. Such experiences are vital for cultivating the creative energy needed to tackle global challenges, from sustainable development to digital innovation [3].

2. A perspective on the direction of STEM education

Looking ahead, STEM education's future is characterized by immense promise and major hurdles. On the one hand, technological innovations are opening exciting possibilities for personalized learning and real-time data-driven feedback. Tools like virtual reality and artificial intelligence enhance traditional teaching practices and foster environments where students can experiment, fail, and ultimately succeed in new and creative ways in classrooms all around [4].

Industry applications further underscore the importance of these educational adjustments. For example, companies in sectors such as advanced manufacturing and renewable energy increasingly rely on graduates who possess both technical skills and the ability to work across disciplines. In many cases, partnerships between educational institutions and industry leaders are forging pathways that ensure students acquire practical experiences and remain agile in a competitive global market. These collaborations have demonstrated that when STEM education aligns with real-world needs, it becomes a powerful engine for innovation and economic growth [5].

Still, amid these positive trends, challenges persist. Disparities in access to quality STEM education continue to mirror broader social and economic inequalities. In many regions, inadequate infrastructure and limited technological resources hamper progress, leaving some students disadvantaged. Moreover, persistent gender gaps and underrepresentation of marginalized communities in STEM fields indicate that systemic barriers must be overcome to achieve true inclusivity [6].

Addressing these challenges requires a collective commitment to transformative change. It calls for educators, policymakers, and industry stakeholders to work hand in hand, developing inclusive strategies that bridge gaps and nurture talent from all backgrounds. As we reflect on these imperatives, we recognize that the future of STEM education is a shared journey—a continuous process of innovation, adaptation, and collaboration.

In embracing this journey, we are invited to adopt a perspective that is both critical and hopeful. Integrating advanced technologies with progressive pedagogical practices can enhance learning outcomes and inspire a generation of problem-solvers poised to address the most pressing issues of our time.

3. Advancing STEM education

Technology is crucial in developing STEM education and making it more accessible. Innovative strategies involving artificial intelligence, virtual and augmented reality, robotics, and online learning platforms have transformed how STEM subjects are taught and learned [7]. These technologies provide interactive and immersive experiences that enhance student engagement and comprehension of the subject content. For example, educational robotics is increasingly being used to introduce problem-solving and computational thinking skills to students at an early age [8]. More recently, it was determined that using AI technologies, such as computer-based personalized learning environments and interactive robot tutors, stimulates students' curiosity and maintains their interest in STEM learning [9]. Additionally, digital learning environments advance greater inclusivity, particularly for students in remote or underserved communities [10].

Similarly, instructional strategies such as flipped classroom models and blended learning approaches enable personalized education, allowing students to learn at their own pace [11]. In a recent study, Zhu [12] affirms that personalizing instruction is one of the most effective instructional strategies. Zhu's ([12], p. 261) study also found that other effective instructional strategies in STEM education are "active learning", engaging learners, providing feedback, "building a learning community", and "clarifying learning objectives". Importantly, educational robotics has been found to improve teaching and learning and, hence, advance STEM skills [13].

4. Building a sustainable STEM ecosystem

A strong STEM education ecosystem requires collaboration among various stakeholders, including governments, educational institutions, industry leaders, and non-profit organizations [14]. Governments play a critical role in formulating policies supporting STEM education, while industries provide real-world applications, mentorship opportunities, and funding for research and development. Educational institutions are the foundation for STEM learning, ensuring curricula remain relevant and aligned with industry needs.

Furthermore, informal learning environments such as science museums, maker spaces, and extracurricular STEM programs contribute significantly to furthering curiosity and innovation among students [15]. A multisector approach that includes public-private partnerships and community engagement is essential for sustaining a robust STEM education framework that prepares students for future challenges. Designing a STEM education curriculum for teacher education is an important aspect of developing STEM education [16]. Preparing students for future challenges contributes to achieving the United Nations 2030 Agenda for Sustainable Development, specifically, SDG 4, encouraging quality education and lifelong learning. While all other SDGs are important, they depend on SDG4.

5. Conclusion

As we head toward the future, STEM education must change to satisfy society and industry's ever-changing demands. Addressing equitable access, curriculum modernization, and workforce alignment will require sustained efforts and innovative solutions. We can build a more inclusive, dynamic, and future-ready educational system by learning from successful STEM education models worldwide and adapting best practices to local contexts.

This book provides insightful analysis of the present situation and future directions of STEM education by means of a collection of research, case studies, and viewpoints from educators and scholars across the globe. Through these discussions, we aim to add to the continuous initiatives to bridge the future of STEM learning, ensuring that students everywhere are armed with the skills and knowledge they need to thrive in the twenty-first century.

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Chapter 2

Perspective Chapter: Mathematics for Teaching – It's Not (Just) Pedagogy

Ann Kajander and Lynda Colgan

Abstract

The specialized mathematics content knowledge that is required for effective teaching is multidisciplinary and non-trivial, and the subject of multiple, typically nonspecific interpretations. The purpose of this chapter is twofold: to provide a scalable definition of mathematics knowledge for teaching (and learning), and posit a new conceptual framework, informed by the constructs, assumptions, expectations, beliefs, and theories that differentiate the distinctly *mathematical* aspects of this type of teacher knowledge. To do so, we build on Shulman's original conception of *pedagogical content knowledge*. By using a lens drawn from our own critical practice as mathematics educators, we articulate a working definition which is clear enough to catalyze the development of re-imagined and robust mathematics teacher education standards, programs and courses. By extension, we call upon post-secondary institutions to provide interdisciplinary environments in which "translational" skills and processes are nurtured and developed. We adapt the term "translational" from healthcare to describe an integrated teacher education program that would aim to train a new generation of "hybrid" mathematician/educators to be effective translators of mathematics; mathematics education research; and their intersection across audiences. By experiencing how classroom-focused mathematics and cognitive/pedagogical sciences intersect, the graduates of translational mathematics education programs will be uniquely equipped to deliver improved instruction resulting in increased student achievement.

Keywords: mathematics for teaching, teacher mathematics knowledge, mathematics teacher education, pedagogical content knowledge, specialized content knowledge

1. Introduction

This chapter is offered as part of the on-going efforts in teacher education to determine teachers' needs related to their mathematical understanding as needed for effective teaching. In our own work, we have encountered conflicting views on what background and course work are needed in the preparation of effective elementary and secondary teachers of mathematics, and confusion as to what aspects are seen as "mathematical" and what aspects are "pedagogical," "cognitive," "instructional" or "developmental." And if indeed, as is now generally recognized, that teachers' understandings of mathematics for the purposes of teaching are indeed specialized, how can such aspects be more precisely described and defined, other than by saying that content knowledge is *special* or *distinct* and requires focused preparation programs centered around specific knowledge and competencies. What are these mathematical competencies?

2. Rationale

Our reasons for focusing on a re-examination of the mathematics and mathematical processes (such as reasoning and representation) inherent in Kindergarten to Grade 12 mathematics curricula; how these should be understood by teachers; and, the implications for teacher education programs, stem from one local factor and one broader, international phenomenon.

As of February 1, 2025, all teacher applicants and internationally educated teacher applicants seeking certification in our Canadian province of Ontario will be required to pass a *Math Proficiency Test* (MPT) in order to apply for licensure through the Ontario College of Teachers (OCT)[1]. Any individual seeking certification to teach in Primary (K-Grade 3), Junior (Grades 4–6), Intermediate (Grades 7–9) or Senior (Grades 10–12) curricular divisions (including those with 'teachable' subjects which do not include mathematics), will need to pass this test of fundamental mathematics skills (including content up to Grade 9) and curricular components (instruction, differentiation and assessment). The motivation for the mandatory mathematics test for new teachers is not only to improve Grade 3, 6 and 9 students' achievement on annual standards-based mathematics evaluations, but also because all certified teachers in Ontario, regardless of their teacher education program (Primary/Junior, Junior/Intermediate or Intermediate/Senior) could possibly be assigned to teach mathematics to students in Grade 6 or below and in some cases, assigned to teach Grade 7 to 12 mathematics [1][2]. While we agree with the principles of credentialling mathematics teachers, echoing the sentiment of Deborah Ball who once said "teachers must know the subject they teach. Indeed, there may be nothing more foundational to teacher competency," [2] we, like others in agreement, have been harshly criticized,

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[1] Although new to Ontario, Canada, passing a standardized test of reading, writing and mathematics is a basic requirement for teacher certification in almost all 50 states in the USA. These qualifying tests attempt to measure a prospective teacher's knowledge and skills and are used by most public schools in the United States to ensure that educators are qualified to teach. It should be noted that because each individual state sets its own standards, testing requirements vary on a state-by-state basis. In Canada, no other province has a qualifying test as a requirement for teacher certification; however, a few universities (Lakehead University (Ontario) and Memorial University (Newfoundland and Labrador) do have "Math Competency Assessments" or "Math Placement Tests" that are diagnostic evaluations of basic skills in mathematics that must be completed as a condition for graduation or for registering for particular mathematics or mathematics education courses.

[2] Ontario court upholds mandatory math test for new teachers Province initially introduced test in effort to help improve students' math test scores Allison Jones · The Canadian Press · Posted: Nov 28, 2023 1:15 PM EST | Last Updated: November 28, 2023

finding ourselves amid enormous controversy surrounding this new policy [3][3]. The vocal backlash and harsh criticism arguing *against* the test has been, most notably, from teacher candidates, teacher unions and Faculties of Education. Loud support *for* the test has been voiced by other stakeholders (including parents and the Ministry of Education[4]) looking for greater public accountability and teacher professionalism. As provincial assessments by the Education, Quality and Accountability Office (EQAO)[5] continue to report unsatisfactory student achievement scores in meeting the provincial standard over the last few years (about 60, 50 and 54% of Grade 3, 6 and 9 students, respectively), multiple invested parties have demanded swift action and scalable solutions to improve student achievement. Curricula at multiple grade levels are being hastily rewritten and mandated. In other words, new learning for teachers and students, predicated on immediate reforms to pre-service and in-service teacher education programmes to provide timely and relevant teacher preparation for the new content is required.

In trying to formulate arguments to support measurements of mathematics teacher competency, we have found ourselves recurrently struggling to articulate or find satisfactory definitions of what is meant by knowing 'mathematics' in the context of teacher education and classroom practice. In terms of course design, we have argued that mathematics courses for teachers must contain *more* than standard mathematics courses. But what is the "more?" Mathematician Hyman Bass, who by his own admission, has become significantly engaged in school mathematics, states that the "more" is *strictly mathematical knowledge* (not about students or about pedagogy) that proficient teachers need and use, yet is distinct and thus not known by many other mathematically trained professionals, for example, research mathematicians [4]. Like us, Bass argues that this uniquely distinct type of knowledge required by teachers is not something likely to be part of the instruction in content courses for teachers situated in mathematics departments. For example, multiple representations and their associated reasoning *is* mathematics, and yet most research mathematicians would dismiss such content as being "school math," not "deep math," and thus better left to the pedagogues.

These false impressions and egregious simplifications underscore the fundamental, yet elusive distinction between the mathematical knowledge needed for teaching and the mathematical knowledge needed for other occupations or professions in which mathematics is used. The goal of academic mathematics courses taught by research mathematicians seems to be immediate and insular, i.e., individuals in the class need to "know" the content solely for their own understanding and its applications to other domains in science, technology, engineering and beyond. In sharp

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[3] While the first Math Proficiency Test (MPT) was administered in 2021, it was challenged in court as being unfair to racialized teacher candidates and therefore infringed on equality rights under the Canada Charter of Rights and Freedom. In November 2023, an appeal court ruled that the test was not unconstitutional and the plans for administering the test could go ahead. The Proposed Regulatory Amendments related to Proficiency in Mathematics received approval and came into effect on filing on May 30, 2024. The date for the new MPT is effective on February 1, 2025. The Education, Quality and Accountability Office (EQAO) will develop, administer, mark and report on the test results to test takers and OCT.

[4] https://news.ontario.ca/en/release/1002939/province-improving-accountability-and-transparency-in-ontario-schools

[5] EQAO is an arm's length government agency that develops, administers and reports on annual province-wide assessments of Grades 3 and 6 Literacy and Numeracy; Grade 9 Mathematics; and Grade 10 Literacy

contrast, the goal of mathematics courses for teachers is for the candidates not only to "know" mathematics for themselves, but to be nimble in situating and sequencing the content along a K-Grade 12 continuum (i.e., what concepts came before and what comes after); agile in deconstructing the content in order to present it to students in multiple ways using age- and mathematical/developmentally-appropriate approaches and representations together with the associated reasoning; and, anticipate (with the goal of pre-empting) well-documented student misconceptions by calling upon firm foundations in how learning happens. Bass reminds us that novice mathematics teachers' "self-talk" must focus on mathematics, responding to classroom discourse [4], by first asking oneself "What is the significant mathematics happening in my classroom right now?" "What should I be looking for, and be sensitive to, mathematically, in this situation?" and "What are the instructional moves I need to make to shepherd this discussion back to the important mathematics that is the goal of this lesson?" It goes without saying that the elephant in the room is that this specialized, multi- and interdisciplinary content knowledge requires both a highly specialized teaching context and instructor—one who knows and can create experiential opportunities to concretize the intersection of mathematics content, cognition, curriculum, pedagogy and developmental trajectories—and ones unlikely to be found in or the result of current pre-service (or in-service) education programs.

Our second concern arises from the ever-widening net that is used to capture all that falls under mathematics "curriculum." With the explicit inclusion of arguably important issues such as diversity and inclusion; topics such as culturally-relevant mathematics; socio-emotional learning (e.g., foci on mindset, perseverance, risk-taking, relationships, and attitude); and, rapidly-changing recommendations around how to teach (e.g., intentional instruction versus inquiry-based learning), we note two distinctly negative trends: the diminishing focus on and elimination of mathematics content itself, and the failure to differentiate teaching mathematics from teaching in general. We argue that teaching mathematics is distinct from teaching in other subject areas, and that student learning of mathematics cannot be achieved unless mathematics content, developmental and pedagogical principles, and research-based practices in mathematics teaching are inseparable in the learning trajectory of mathematics from Kindergarten to Grade 12. By stretching the curriculum to include financial, data and information literacy, coding and other tangential topics, less time, in an already over-crowded curriculum, can be dedicated to the types of experiences that could improve both the teaching and learning of mathematics.

To address the need for a common understanding of what it means to be a "mathematically qualified educator," we offer an over-arching model for the cumulate body of mathematics knowledge uniquely needed for teaching the K-Grade 12 curriculum. By extension, we argue that by developing an easily interpretable and implementable definition, the need for significant, specific and rigorous learning goals (including standards) for mathematics teacher education programs may lead, not only to more deliberate and appropriate mathematics teacher education course design and implementation, but also to improved outcomes for students along the elementary to secondary continuum, a connection that is well-established in the literature [5].

Both our definition and our recommendations for mathematics teacher education programs are drawn from our own critical practice with individuals—teachers, parents, mathematics educators, mathematicians, administrators, researchers in fields beyond mathematics and students—representing a wide range of perspectives on what change is needed and why. We are advocating for dramatic changes to what is considered to be mathematics knowledge unique to teaching as well as teacher preparation. These proposed changes are not abstract, but rooted in the intersection of our own work with and research involving multiple stakeholders who are impacted by current classrooms and contexts. We propose that the ideas proffered in this chapter are the outcomes of genuine critical practice based on the analysis of our own communities of practice and research. By synthesizing the perspectives of a diverse network who have been trying to transform mathematics education practically, but separately, we integrate many voices collectively.

3. Background

We are mathematics educators, one with a secondary mathematics classroom teaching background and one whose focus has been on elementary mathematics education, respectively. We bring disparate, yet rich and formal knowledge of mathematics content, mathematics education research and a shared belief that higher expectations bring higher achievement, regardless of the age of the learner. Separately, in the context of multiple studies and professional self-assessments, we have amassed data in the form of qualitative and quantitative surveys, individual and group interviews, paper and pencil tests, and annotated observations, of over 1000 prospective teachers as they work to understand the mathematics that we believe they will need for effective teaching.

Advocating for required coursework has been a career-long endeavor for the first author in particular, having begun teaching mathematics courses for prospective elementary teachers in 1989— in a mathematics department—and continuing to do so to the present time in a faculty of education. Similarly, in her first year as a Primary/Junior instructor at a Faculty of Education—1998—the second author was allotted 12 course hours in which to "prepare" teacher candidates to teach and assess students using the mathematics curriculum policy document required for Kindergarten to Grade 6. With her influence, by 2021, the course was increased to 60 hours over three academic terms. As professional colleagues, we have long reflected on and discussed the benefits and detriments of mathematics "education" courses, when some are offered by mathematics departments in Faculties of Arts and Science, and others, by Faculties of Education [6].

With courses commonly offered in two different faculties by different categories of scholars, i.e., research mathematicians versus education staff (ranging from tenured faculty members to graduate teaching fellows with no classroom experience and no mathematics education specialization), it is not surprising that there has been and continues to be confusion at the institutional level about *who* "owns" mathematics education, decisions around *what* it should comprise, and *why*. Moreover, there is no agreement on precisely what constitutes "mathematics education" in the context of teacher preparation and professional development over the long course of educators' careers. Over many years and in multiple contexts, including local, national and international mathematics education conferences, when the topic of mathematics for teaching arises, we have encountered a common barrier: there is a pervasive perception that the mathematical knowledge, problem solving, reasoning, perspectives, and resources that we, as mathematics educators with strong mathematics backgrounds, deem to be most important for mathematics teacher education courses, are looked down upon and dismissed as mere 'instructional pedagogy topics' by both institutional administrators and research mathematicians (even some who purport to have an interest in mathematics education). The content of the highly specialized mathematics course work foundational to and essential for mathematics teacher preparation is not recognized as an aspect of mathematics, valued for being rich and multidisciplinary, nor considered to be complex and interdisciplinary to teach. Furthermore, the defining qualities of the rare instructor who can teach such courses effectively, continue to be unspecified by hiring teams in Education and Arts & Science, resulting in increasing numbers of new mathematics education faculty who have a targeted interest in topics like children's literature with a mathematics theme, "unplugged coding," or diversity, (the list goes on), but lack mathematics, developmental psychology, cognitive science and pedagogy, or are research mathematicians who "dabble in education" but lack the strong interdisciplinary background needed to prepare and support teachers.

Our goal here then, is to adapt the Translational Institute in Medicine (TIME) model. The mission of TIME is to enhance collaboration and optimize communication by sharing expertise. This is achieved by offering a curriculum that interweaves rigorous research with authentic "clinical" experiences in a multidisciplinary environment that crosses departments and disciplines.

Notwithstanding the important contribution of the rich "mathematics for teaching" framework described by Ball and colleagues [2], our focus is to drill down deeper into particularly the specialized content knowledge aspect of the Ball et al. model, using the original Shulman conception of pedagogical content knowledge [7] as the framework to posit a *Translational Institute in Mathematics Education* curriculum for mathematics teacher education.

4. Framework

Perhaps the most oft-cited model of mathematics for teaching was created by Ball and colleagues [2]. These authors identify a number of sub-domains that fall under two main headings, i.e., subject matter knowledge and pedagogical content knowledge. While we appreciate the model's comprehensiveness, the two major domains and their respective subdivisions can be overwhelming and may contribute to a lack of clarity in designing mathematics courses for educators. For example, the "subject matter knowledge" domain is further distributed across three subdomains, namely common content knowledge, specialized content knowledge, and horizon knowledge. Of particular interest to us is the "specialized content knowledge" piece of the model. While we realize that the other category in the model, "pedagogical content knowledge" (to use its terminology) still draws heavily on mathematics in lesson design, responses to students and so on, our goal is to add clarity to what content *mathematics* courses for teachers, framed in the subject matter knowledge part of the model, should constitute, and hence we draw particularly from the specialized content knowledge category, and attempt to further articulate its description.

According to Shulman, the mathematics content a teacher should know includes:

1. The most useful forms of representation of the concepts and topics.

2. The most powerful analogies, illustrations, examples, explanations, and demonstrations of those topics and concepts.

3. The ways of representing and formulating the content that make it comprehensible to others [7].

Shulman continues by saying that "since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation" ([7], p. 9). Importantly, the reference to the key roles played by mathematical representation appears over and over in the Shulman description above, and in fact, throughout his 1986 paper. Indeed, the knowledge of representations and their associated mathematical reasoning is a particularly important, but often weak, area of understanding for prospective teachers [8].

A challenge we have encountered repeatedly, is the (mis)interpretation of the mathematical ideas of representation and reasoning, and the (mis)perception that these ideas are really 'pedagogy,' and should thus be housed in education curriculum and instruction courses for teachers. We fundamentally disagree.

5. Goals

To follow we illustrate and describe the rich mathematical nature of the representations repeatedly mentioned by Shulman [7], and the deep (and developmental) reasoning which ensues, using several examples. We further argue, based on a large dataset, that while such mathematics *has* to be provided during curriculum and instruction courses if no other mathematical course options for teachers are available, that much better results can be obtained if prospective teachers have the opportunity to focus on these particularly *mathematical* concepts, either prior to or concurrently with curriculum and instruction (informally, 'methods') courses. Prospective teachers viewing a sample lesson, for example, who do not have the required knowledge of the representations and models involved, will typically miss many of the important pedagogical aspects in their quest to sort out the mathematics [9]. This contrasts with participants who are already familiar with the mathematical ideas who can focus on the lesson itself at a higher level.

To avoid confusion with existing models, we will term the specialized mathematics concepts needed by teachers for effective teaching as *specialized mathematics for teaching*, or SMT. To follow, we attempt to problematize, illustrate, and define this term in a useable way. We begin with addressing some preconceived notions and common problems, first by offering a series of vignettes drawn from our research and other experiences.

6. Math for teaching: what's the problem?

To follow are several scenarios illustrating some of the challenges in describing and understanding SMT, which also illustrate the perceptions of some sample stakeholders. They are offered as a collective, with discussion to follow. In each case, the reader is invited to ponder the problem illustrated. Each vignette has been chosen to illustrate a particular challenge with the conceptualization of the field of specialized mathematical content knowledge for teaching.

6.1 Story one

A research mathematician and mathematics educator are chatting at a conference, looking at new mathematics manipulatives. The manipulatives in question were rectangular prisms made of plastic to represent base ten blocks. The mathematics educator is quite excited by these, as the shapes are exactly proportional – a tray of ten 'ones' is used to illustrate 10, and the tens tray is proportional to the unit piece. Similarly, a tray of ten 10's, the hundreds tray, is proportional to both ones and tens. Commonly used base ten blocks do not have this self-similar property.

The mathematician is unable to understand why the mathematics educator is excited … and after an explanation of the need to represent multidigit numbers in concrete, highly visual, accessible and accurate ways to preservice teachers by the mathematics educator, the mathematician comments "but cannot they just see these things in their head?"

6.2 Story two

An important representation of the operation of multiplication is the area model. The area model can be used in elementary grades to develop whole number products, such as 12 × 13, with flexible understanding. We take it as a given that this model is an example of the kind of specialized mathematics for teaching, SMT, that we are describing here. Having said that, we have observed that teacher candidates with formal post-secondary mathematics backgrounds know a 'rule' for simplifying the product of two binomials such as $(x + 2)(x + 3)$, yet are unable to explain developmentally why this method—as well as the other possible simplification methods—make sense and could contribute to children's computational fluency and calculational flexibility. In fact, many seem to be unaware of the area model for whole number multiplication.

6.3 Story three

This story took place in a grade 2/3 classroom. The teacher was providing examples of division questions on a smart board to the children. All the examples presented by the teacher were of the style "a case of 24 apples is divided equally between 4 charity baskets. How many apples should go in each basket?" The children were given about six such examples, all using this same model of division (sometimes called 'equal sharing' or the 'partitive' model of division).

This was followed by a worksheet. The first question on the worksheet asked the children to use a drawing of 12 circles to illustrate 12 ÷ 6.

First, the teacher was approached by two boys who had drawn the following (**Figure 1**):

The teacher told the boys they were correct.

Next, a pair of girls showed her their picture, as below: (**Figure 2**)

The teacher 'corrected' the girls' picture to look like the boys' picture. One of the girls began to cry, in obvious frustration.

Figure 1.
The boys' model drawn to illustrate 12 ÷ 6.

Figure 2.
The girls' model drawn to illustrate 12 ÷ 6.

6.4 Discussion of the stories

The first story illustrates a situation which is deeply problematic but often disregarded in course development. Understanding the starting point and needs of teacher candidates is crucially important. A "top down" approach in which it is assumed that candidates have experienced their own K-Grade 12 mathematics education in conceptual ways, and can call upon 'learned' visualizations illuminating the reasoning behind the ideas to lead the kind of instruction in which children develop mathematical ideas using concrete tools and other representations, is neither realistic nor helpful. Indeed, such an approach can further exacerbate the pervasive sense of elementary teachers that they aren't good" at mathematics [6]. And even teacher candidates who do have significant mathematical background often are unaware of suitable developmental progressions for learning, or in this case, the uses, benefits, pitfalls, and overall nuances of classroom manipulatives and other representations, and how these connect to, and support, developmental reasoning [10].

The second story further illustrates how easy is it to overlook the developmental thread of an idea, when approaching it from a more abstract perspective as well as the idea that post-secondary mathematics courses can replace the need for SMT. Our data consistently illustrate that the conceptual underpinnings of typical procedural calculations are poorly understood by many prospective teachers [11], even those with strong mathematics backgrounds [12], and that exploring with manipulatives is often an important key to progress [9]. The related problem is the difficulty, especially for a more sophisticated mathematical knower, to unpack the levels of understanding and abstraction needed to prompt developmental understanding. For example, we have heard teacher candidates with post-secondary mathematics backgrounds, who are asked to explain an idea conceptually, claim that a higher-order (typically formulaic) algebraic 'explanation' *is* how they 'understand' an idea.

Specifically in the case of the mathematics in Story Two, both whole number products, and binomial products, can be understood and connected using the area model. Yet the traditionally-taught algorithm for whole number multiplication begins with the units, for example the '2×3' sub-product in an example such as 12×13, while the typical North American algorithm for binomials, 'FOIL' begins with the left-most quantity, so for the example provided here, $(x + 2)(x + 3)$, it leaves the '2×3' calculation to the last. An 'aha' moment often comes when teacher candidates realize these methods rely on the same representation, and either one can proceed in any order. Once again, we emphasize that this is a *mathematical* realization.

Furthermore, teacher candidates subsequently begin to see that allowing students to construct, discuss, and then adapt these models to develop their own computational methods can later result in an understanding of an abstraction of the initial idea (in this case, abstracting the whole number area model to one showing multiplying expressions with variables) as a generalization of something they already understand. Such opportunities may also open the door to respecting that the traditional algorithm used in North America is merely one of many "non-standard" models developed by different cultures to calculate the products of multidigit numbers. Ultimately, the same area model can be further exploited to develop factoring techniques, and even the quadratic formula [13], and these constructs are often "newsflashes" to intermediate–senior teacher candidates taking mathematics courses for prospective high school teachers.

Story three is disheartening, yet sadly representative of similar events played out over and over in classrooms we have observed. The girls' model was in fact the 'correct' representation of $12 \div 6$, based on the model of the division operation illustrated by the contextual examples provided by the teacher earlier. The examples shown by the teacher used the 'equal sharing' or 'partitive' model of division, i.e., the idea of evenly dividing an amount into equal groups. The boys, on the other hand, were using a different interpretation of division, sometimes called the measurement or quotative model, in which the second number refers to the *size* of each group (not the *number* of groups). We are not clear (unless due to gender bias) as to why the teacher also switched her understanding from partitive to measurement along with the boys—at any rate she seemed totally unaware she had done so. Another explanation is that perhaps the teacher subconsciously assumed that circling two groups of 6 dots was quicker than circling six sets of 2 dots. At any rate, both sets of students' representations were 'correct' but in fact the girls' model adhered more closely to the provided classroom examples—it certainly wasn't 'wrong' as the teacher indicated to them.

The point here is that SMT is rich, subtle, contextual, developmental, and nontrivial. It needs to be explicitly studied and learned, in order to be used effectively in classroom teaching; moreover, the higher level of mathematical learning an individual has attained, may require more unpacking and purposeful developmental reconstruction of concepts.

7. Discussion of the construct of SMT

The three chosen vignettes illustrate several aspects of SMT. The first is that SMT is fundamentally based on *representation and reasoning*, as initially posited by Shulman. Often, suitable representations need to be specifically learned and studied, especially in cases where prospective teachers' backgrounds are very traditional and procedurally-based. As well, teachers often need a range of representations in their toolkit, not all of which they have necessarily seen before.

Secondly, as discussed, SMT is deeply *developmental* in a *mathematical* sense. That is, the knowledge of what concepts and representations must already be in place, and how to build on these, is critical. Jumping steps, without attention to the connections and abstractions needed, is not helpful. Nor is using a higher-order abstraction to define a lower order concept [14]. Since multiple representations and various pathways are often possible, teachers need to be aware of these. Seeing the developmental progression from a vantage point of a strong mathematical background adds another layer, in that more and more unpacking is needed, as well as attention to what (mathematical) building blocks are needed.

The third example illustrates just how rich, complex and nuanced such understanding of mathematics must be. While many pedagogical factors might also be drawn from the last example, the fact remains that it was the teacher's narrow *mathematical* understanding of division models that derailed the interaction with the girls; sadly, such experiences, felt over and over by students, can not only powerfully sow the seeds of mathematics anxiety, but result in enduring misconceptions.

8. Defining SMT

According to the Purdue University online Writing Lab, we use definitions to avoid misunderstanding with our audience by introducing the term; then stating the *class* or *object* to which the term belongs; and, finally, expanding on the *differentiating characteristics* that distinguish it from all others of its class. As an illustration of this three-step process, they provide this example: *Astronomy* (term) is a *branch of scientific study* (class) primarily concerned with *celestial objects inside and outside of the earth's atmosphere* (differentiating characteristics).

Defining the "term" *specialized mathematics knowledge for teaching* does not fall neatly into the three-step method because although the term is familiar to most mathematics educators and many mathematicians, it is opaque because of subjective interpretations and evaluations, and in fact, many of the personal definitions that have been posited have only served to increase misinterpretations about what SMT *is.*

The first step in defining *specialized mathematics knowledge for teaching* is to establish that it is a distinct and multifactorial body of mathematical knowledge that stands alone. Although the term contains the words *mathematics* and *teaching*, it involves many more elements than the two italicized words, which in combination bring us closer to a shared understanding—the true purpose of a definition. If we follow the writing centre examples above, we will say that SMT is a branch of scientific study that encapsulates the mathematical, pedagogical, cognitive and developmental knowledge required by educators in order for students to receive a mathematics education that upholds the integrity of both mathematics and the learner.

SMT begins by valuing and knowing how mathematics understanding develops beginning with quantity and counting, the underlying structures of numbers, through to operations, and their physical and mental images. Beginning with our youngest learners, and continuing throughout the school years including the secondary grades, SMT prioritizes knowledge of appropriate representations and models, and their associated reasoning, as a fundamental factor in SMT. Similarly, while young children perceive shape and space from the world around them, it is the role of the teacher is to advance those perceptions by modeling and providing opportunities for students to mathematize and formalize their earlier knowledge and communicate it with precision. In order for students to transfer lower-order mathematical ideas from one context to another and recognize the connections/relationships that result in a "bigger picture," they must build upon carefully orchestrated prior knowledge then begin gradually to construct the higher order ideas we call mathematical generalizations. This is what is meant by "mathematically developmental." The teacher must carefully negotiate the trajectory towards higher-order mathematical constructs, by calling upon and offering concrete models, illustrations and related explanations that bridge to more abstract representations, and lead, ultimately to a generalization. The reasoning involved must rely only on constructs students already are comfortable with, not, as is often unwittingly done in mathematics, by drawing upon unfamiliar higher-order ideas. Without knowing how, when, and with what representations mathematics learning happens in the students' minds, the introduction of new mathematical content/concepts is futile.

The selection and use of representations is much more than the mere drawing of an outcome—these skills and processes are part of the tangible and cognitive toolkit learners acquire, then use, to explore, reason, and abstract. Teachers must be deeply aware of the suitability of a range of such tools for a given task, as well as the mathematical appropriateness and possible uses and pitfalls. Often teachers need variety of representations, including drawings and manipulatives, and an awareness of the characteristics of each for different purposes. For example, why is the Soroban (Japanese Abacus) a powerful extension of finger-counting, and five- and ten-frames? Why is the Soroban a powerful tool for concretizing place value beyond base ten blocks? When is the number line more useful in exploring integer operations and when are integer counters a safer choice? What are the benefits of using different fraction manipulatives (ranging from fraction strips to grid paper) for exploring different operations? When are concrete algebra tiles most useful and when are online options helpful?

Teachers also need an understanding of the various interpretations and models of the fundamental operations (for example, the partitive versus the measurement model of division) and how and where these interpretations are relevant, as well as which of these models must be in place before proceeding with a new idea. As an example, teachers interested in having students explore the results of dividing by a unit fraction such as in 2 ÷ ¼ need to ensure students already are familiar with the measurement model of division ("I have to measure two cups of flour but only have a ¼ cup scoop, how many scoopfuls do I need?"), while exploring a calculation such as ¼ ÷ 2 ("I want to share the remaining ¼ of a pizza with my friend"), requires familiarity with the partitive model. Similarly, exploring $(-6)\div(-2)$ is very straightforward if one is familiar with the measurement model of division but nearly impenetrable without it.

This knowledge is rich, complex, nuanced, connected, flexible, deeply mathematical, and non-trivial, usually contextualized in the business of teaching, yet learnable as a discipline in its own right. While such knowledge enables good pedagogy, it is deeply mathematical.

Knowledge of possible connections should extend up to as well as beyond the relevant grade level, as some students may be working at differing levels of generality and formality of a mathematical concept. It is also important that teachers have a sense of what is to come in terms of how some ideas are approached. For example, exploring division by zero as a process is much more productive when the student is at an appropriate developmental age for contemplating the complexity and has not, at a younger age, been "brushed off" by brusque 'rules' such as, "You cannot do it. It's undefined." Such deep knowledge of specialized mathematics for teaching includes not only an understanding of the related horizon knowledge, but also the mathematical underpinnings upon which understanding is constructed. Thus, horizon knowledge should extend to grades previously as well as those to come.

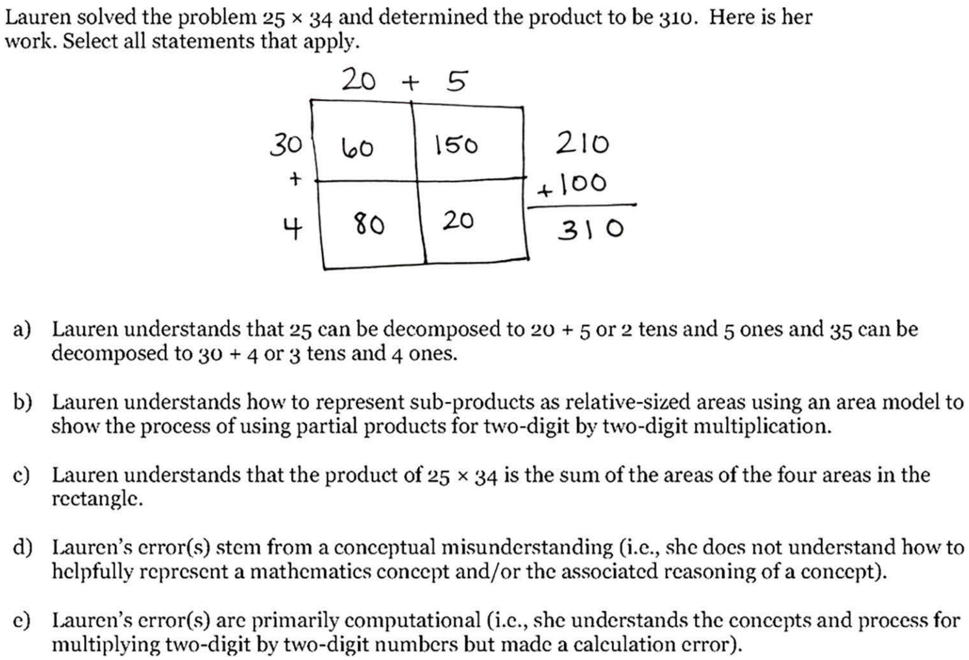
Knowledge of the mathematically conceptual building blocks of an idea is a critical component of SMT. Yet again we emphasize that this is *mathematical* knowledge, but of a distinct nature, although certainly fundamentally important for good pedagogy.

9. Assessment

We often hear that such specialized knowledge of mathematics would be difficult to assess, particularly in large-scale tests. Ball and her colleagues have created a wealth of multiple-choice items mainly for elementary level teachers, some of which attempt to measure aspects of what we are terming SMT. We have, over the years, crafted a wealth of such items as well (e.g. [9, 11]), both open-ended and multiple choice, spanning a range of grades. For illustrative purposes in the current discussion, a set of examples of assessment items is provided to follow, crafted to span a range of grades and question styles.

9.1 Examples of assessment items

The figures that follow are simply illustrative, offered to dispel arguments that SMT is too "hard" to assess. Further items have been used and studied in our other work (**Figures 3**–**5**) [9, 11].



Lauren solved the problem 25 × 34 and determined the product to be 310. Here is her work. Select all statements that apply.

a) Lauren understands that 25 can be decomposed to 20 + 5 or 2 tens and 5 ones and 35 can be decomposed to 30 + 4 or 3 tens and 4 ones.

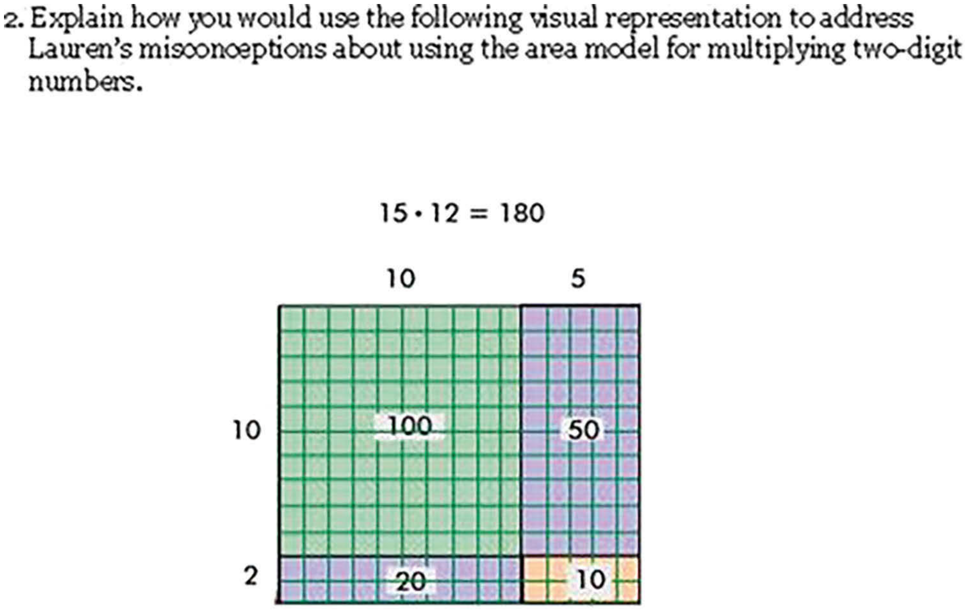
b) Lauren understands how to represent sub-products as relative-sized areas using an area model to show the process of using partial products for two-digit by two-digit multiplication.

c) Lauren understands that the product of 25 × 34 is the sum of the areas of the four areas in the rectangle.

d) Lauren's error(s) stem from a conceptual misunderstanding (i.e., she does not understand how to helpfully represent a mathematics concept and/or the associated reasoning of a concept).

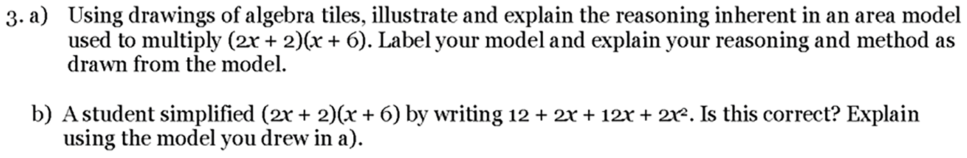
e) Lauren's error(s) are primarily computational (i.e., she understands the concepts and process for multiplying two-digit by two-digit numbers but made a calculation error).

Figure 3.
Sample of a multiple choice assessment item to assess SMT.



2. Explain how you would use the following visual representation to address Lauren's misconceptions about using the area model for multiplying two-digit numbers.

Figure 4.
Sample short response assessment item to assess SMT.



3. a) Using drawings of algebra tiles, illustrate and explain the reasoning inherent in an area model used to multiply $(2x + 2)(x + 6)$. Label your model and explain your reasoning and method as drawn from the model.

b) A student simplified $(2x + 2)(x + 6)$ by writing $12 + 2x + 12x + 2x^2$. Is this correct? Explain using the model you drew in a).

Figure 5.
Sample extended response item to assess SMT.

We have, in our work [9] seen the connection between deeper understanding of SMT as measured by items such as the samples provided above, and higher-quality mathematics teaching. Hence we suggest that SMT can both be improved with suitably focused coursework, which is critically necessary for all prospective teachers of mathematics including those with formal mathematics backgrounds, and it can also be measured and assessed with reasonable effectiveness.

10. Implications for courses for teachers

In 1986, Shulman queried educational researchers about why it was that “no one asked how subject matter was transformed from the knowledge of the teacher into the content of instruction” ([7], p. 6). Now, almost 40 years later, that question remains unanswered and the absence of subject matter in the study of teaching and learning remains what he labeled “the missing paradigm” ([7], p. 6).

Shulman reminds us that the educator must know the “most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others” ([7], p. 6).

There is abundant research to prove that an undergraduate degree is an inadequate pre-requisite for the classroom [15]. Were that true, then every graduate with a mathematics degree should be able to demonstrate the highest levels of subject matter competence, argues Shulman, which is, to *teach* the subject [7]. The truth is that a post-secondary education in mathematics is about the subject of mathematics, not education.

As a profession, education, specifically mathematics education, must then deliver a program that bridges the chasm between knowing mathematics oneself and knowing it for teaching: holding as its standard the fundamental principle that the defining characteristic of pedagogical accomplishment is knowledge of content [7]. This will require a major pivot because the culture of most mathematics education courses is **not** to concentrate on mathematics content—numbers and operations (including place value and fractions), algebra, geometry, and data and probability. While true in our home province of Ontario, the phenomenon is widespread. In fact, two studies by the National Council on Teacher Quality (a US body) found

> *…that just 13 percent of the 860 undergraduate elementary teacher preparation programs reviewed covered critical math topics, including numbers and operations, algebra, geometry, and data and probability [16]. And in 2018, a similar review of graduate programs by NCTQ found that just 1 percent of 201 programs covered these topics [17]*

Much of what we have defined as specialized mathematics content knowledge is what Dan Lortie called the crucial "backstage" skill set that teachers possess and apply on the "frontstage" known as the classroom [18]. By this, Lortie meant having the knowledge and schemata that transform a person from being a subject matter "knower" to a subject matter "teacher."

If we agree with educational psychologists like David Berliner, then we must acknowledge that domain-specific knowledge is a characteristic of an expert in any field [19], including the mathematics teaching profession. The development of expertise requires time, appropriate mentorship, and the integration of disciplines and "laboratories" across which and in which knowledge translation occurs. This last sentence clearly describes the rich preparatory program that already exists in the innovative Translational Institute in Medicine (TIME) model, and one upon which the criteria proffered by Shulman, Berliner, Ball, Bass and others could be actualized given its interdisciplinary nature of linking coursework from multiple specializations with periods of formal observation to enhance the development of professional thinking and action.

Although the TIME model is currently aimed at graduate (M.Sc. and Ph.D. students), the program of 12 courses (three of which are mandatory and three of which are elective), could be adapted to a 3-or 4 year *Translational Institute in Mathematics Education* program that "packages" courses that would include mathematicians, pedagogues, psychologists, cognitive scientists, neuroscientists, qualitative researchers and experienced mathematics classroom teachers. By so doing, pre-service students would develop, over a rigorous, research-based and holistic preparatory experience, the foundational knowledge and practical experiences that are pre-requisite for the mathematics classroom.

As with the TIME program in medicine, over an extended professional program, in the mathematics education derivative program, novice teachers will find themselves in focused seminars with expert academics from multiple fields whose research illuminates mathematics as well as its teaching and learning. They will then be tasked with integrating constructs, theories and content by reporting back and reflecting on the immersive observational opportunities where they experienced expert teachers engaged in the complex exercise of "teaching" while novice elementary and secondary school-aged students endeavor to "learn." Unlike many current teacher education programs, in which learning to teach is the cursory "add on" after graduating with a general undergraduate degree, in a *Translational Institute in Mathematics Education* program, teacher candidates' learning would be unified and purposeful from the start. All classes, whether in geometry or child development, will be conducted with complementarity[6], not in parallel stream, so that future educators learn not only about mathematical content but experience, from the "other side of the desk," the mathematical trajectories, advantages and pitfalls of lessons taught with concrete materials during authentic activities and lessons with peers and school-aged students. They will experience and in turn, acquire, techniques to formulate questions that will prompt mathematizing of content. They will "play" with the "thinker

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[6] The notion of complementarity comes from Physics. The term was coined by Neils Bohr to explain that some phenomena can only be understood when one considers more than one description of that phenomenon using different lenses because the characteristics cannot be observed simultaneously using one definition. It is only when the differences in perspectives and definitions are combined, that the phenomenon can be fully accounted for.

tools" commonly called manipulatives to see how mathematical explanations using multiple representations move from concrete to abstract. Through careful monitoring and questioning by the instructor, and in-depth sharing with peers, both the developmental progression of the mathematical ideas, and the alternate routes for these to emerge, will be explored and unpacked. Through this process, candidates will encounter their own misconceptions or gaps in understanding the mathematical development process and apply their problem solving through the hard task of promoting students' understanding, learning to orchestrate their way through children's misconstructions and remediating accordingly.

Such outcomes are not achievable given the typical requirement of one or two courses in mathematics education offered in our province's consecutive (post-degree) teacher certification program. We argue, that in their current format of generic "education" courses, "concurrent" education programs, running in a totally disconnected stream from Arts & Science or Engineering degree requirements, for example, are also largely inadequate.

We have had good results from offering at least one course in mathematics for teachers (using our SMT definition) prior to explicitly focusing on more typical pedagogical topics such as lesson design and assessment. We have found [9], that even short content-rich, representation-focused experiences are effective in influencing the values of prospective teachers [11] in terms of what is important for students to know, and how they might begin to nurture such student understanding. Imagine, then, the impact of an extended, immersive TIME program.

11. Conclusions

Given that teachers' knowledge of the conceptual underpinnings of mathematical concepts has a direct influence on student achievement [5], a concerted effort to define more clearly and articulate SMT has been the purpose of this chapter. Unclear articulation and ongoing (mis)understandings of prospective teachers' mathematical needs has been a problematic theme throughout both of our careers and continues virulently in our region. Inadequate teacher preparation in mathematics can only result in unsatisfactory mathematical learning by students, ultimately giving rise to what is commonly referred to as "math anxiety" in both students, and eventually their teachers. In our experience, prospective teachers who define themselves as "anxious" about mathematics are adamant and rational about the issue: they know they do not understand mathematics well enough to teach it, and they are fully aware of this problem yet are prepared to head into a classroom where they will be solely responsible for teaching mathematics, after the most cursory preparation. Fortunately, when supported in developing a fuller understanding of mathematics (at least of a few overarching concepts), such conceptions of themselves can change greatly. Indeed, the positive transformation, both mathematically and in terms of self-efficacy, can be quite remarkable, but is unfortunately limited to only a few teacher education faculties who have SMT as a focus and thus, beneficial to only a handful of graduates. The "anxious" students become the new "anxious" in-take in education programs, i.e., the ones who ask, "I'm going to be in your mathematics education course starting in September. We're just going to learn how to *teach* math, right? We're not going to have to *do* math are we?" Sadly, it is not an exaggeration to say that we both keep tissue boxes on our desks.

We can break the cycle but only if we give teachers the confidence to assume their roles in the mathematics classroom—in other words, beginning with the end in mind, which is, in our opinion, a teacher whose SMT is not in question. A teacher who understands how representations—including manipulatives, drawings, other models, virtual environments, or even at times, movement or hand motions—can be used to support the development of particular mathematical ideas. A teacher who understands how mathematical ideas themselves evolve and require different tools across the grades, yet build upon each other in increasingly sophisticated and ultimately abstract ways. And a teacher who understands that supporting the learning of this content requires new types of problem-solving strategies and reasoning.

We offer our conception of SMT to define the "vision of the mathematics teacher," by describing the skills and knowledge teachers should embody and exemplify on graduation from a mathematics education program. We believe that this will be useful in the promotion and creation of better program design, and course design, particularly mathematics for teachers' course content, all of which would ultimately result in improved mathematical understanding for students from Kindergarten to Grade 12.

Based on earlier concepts of Shulman, and further articulated by Bass and colleagues, we have described specialized mathematical content for teaching as a distinct mathematical domain, with unique requirements, which are tied directly to the student learning process and informed by multiple fields of academic study.

It's about TIME (literally and figuratively) for SMT to be an important requirement in mathematics teacher education. As we have argued above, such teacher knowledge is a critical component of classroom mathematics learning for students. If the academic and "clinical" standards for and preparation to be a mathematics teacher—a highly specialized profession regardless of the grade and age of the students—are to shape positive change in the post-secondary education lecture hall or Grade 3 classroom, there is no time to waste.

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Chapter 3

Enhancing Mathematics Education through Flipped Classroom Approaches: Insights and Best Practices

Felix Egara, Mogege Mosimege and Moeketsi Mosia

Abstract

Mathematics education plays a pivotal role in the development of Science, Technology, Engineering, and Mathematics (STEM) competencies, yet traditional instructional methods often fail to fully engage students or accommodate diverse learning styles. This chapter explores the potential of flipped classroom approaches to revolutionize mathematics education, offering insights and best practices for educators. A systematic literature review was conducted to analyze studies on the effectiveness of flipped classrooms in enhancing mathematics education among secondary school learners. The review included empirical studies that reported on implementation strategies, challenges, and outcomes of flipped classrooms in various educational contexts. Drawing on theoretical frameworks and practical examples, this chapter examines the benefits of flipped classrooms in fostering conceptual understanding, problem-solving skills, and student engagement. Through case studies and implementation strategies, educators will gain valuable insights into designing and implementing effective flipped classroom experiences. By embracing innovative pedagogies, such as flipped classrooms, educators can enhance mathematics education and empower students to excel in the dynamic world of STEM.

Keywords: flipped classroom, mathematics education, active learning, pedagogical innovation, STEM education

1. Introduction

Mathematics education serves as a cornerstone in the realm of Science, Technology, Engineering, and Mathematics (STEM), providing the fundamental building blocks for understanding and solving complex problems in various fields. As educators seek innovative approaches to enhance learning outcomes and engage students more effectively, the concept of flipped classrooms has emerged as a promising pedagogical strategy [1]. The traditional model of education often involves instructors delivering lectures during class time, followed by homework assignments to reinforce learning outside of the classroom [2]. However, this one-size-fits-all approach may not always cater to the diverse learning needs and preferences of students. Flipped classrooms offer a paradigm shift by reversing this sequence of instruction, thereby empowering students to take control of their learning journey. In a flipped classroom setting, students are introduced to new concepts and materials before class through online resources, such as videos, readings, or interactive tutorials. Class time is then dedicated to collaborative activities, problem-solving sessions, and discussions, where students actively engage with the content under the guidance of the instructor [3]. This inversion of traditional teaching methods not only fosters a more interactive and participatory learning environment but also allows for personalized instruction tailored to individual student needs.

In this chapter, we explore the potential of flipped classroom approaches to enhance mathematics education. We delve into the theoretical underpinnings of flipped classrooms, discuss their benefits in fostering conceptual understanding and problem-solving skills, and provide practical insights and best practices for implementation. Through case studies and examples, we highlight successful applications of flipped classrooms in mathematics education, illustrating their impact on student learning outcomes and teacher-student dynamics. As we navigate the landscape of STEM education, it becomes increasingly evident that innovative pedagogies such as flipped classrooms hold the key to unlocking the full potential of our students. By embracing this transformative approach, educators can empower learners to not only master mathematical concepts but also cultivate critical thinking, creativity, and collaboration—skills essential for success in the dynamic and interconnected world of STEM.

2. Understanding flipped classrooms

In recent years, flipped classrooms have garnered increasing attention as a transformative pedagogical approach in education, particularly in mathematics instruction. At its core, a flipped classroom reverses the traditional sequence of instruction by delivering instructional content outside of class time, typically through online resources, and dedicating in-class time to active learning activities, collaborative problem-solving, and discussions.

2.1 Definition and explanation of flipped classrooms

In a flipped classroom model, students are first exposed to new concepts and materials through pre-class assignments, such as videos, readings, or interactive tutorials, which they engage with independently at their own pace [4]. This self-paced learning outside of class allows students to familiarize themselves with the foundational content and prepares them for deeper exploration and application during face-to-face sessions [5]. During class time, instructors facilitate interactive activities that reinforce and extend upon the pre-class materials. This may include problem-solving sessions, group discussions, hands-on experiments, or simulations, where students actively engage with the content under the guidance of the instructor and collaborate with their peers to deepen their understanding and master key concepts.

2.2 Comparison with traditional teaching methods

Contrasting with traditional teaching methods where instructors primarily deliver lectures during class time and assign homework for independent practice outside of class, flipped classrooms prioritize active learning and student engagement during face-to-face sessions [6]. By shifting the delivery of instructional content outside of class, flipped classrooms maximize in-class time for higher-order thinking skills, application, and collaboration, thereby optimizing the learning experience for students [7]. Flipped classrooms provide a departure from the passive reception of information typically associated with traditional lectures [8]. Instead of passively absorbing content during class time, students are actively engaged in problem-solving, critical thinking, and peer collaboration [9]. This shift in focus from teacher-centered to student-centered learning empowers students to take ownership of their learning and fosters a deeper understanding of mathematical concepts.

2.3 Theoretical framework supporting flipped classrooms in mathematics education

Flipped classrooms are grounded in constructivist learning theories, which propose that learners actively construct their understanding of the world through experiences, interactions, and reflections. One prominent constructivist theory is Jean Piaget's theory of cognitive development. Piaget argued that children actively construct their knowledge through interactions with the environment, going through stages of development characterized by different cognitive structures. According to Piaget, learning is not simply the acquisition of knowledge but rather a process of actively constructing understanding through assimilation and accommodation.

Another influential constructivist theory is Lev Vygotsky's sociocultural theory of learning. Vygotsky emphasized the role of social interaction and cultural context in cognitive development. He proposed that learning occurs within a social context, and individuals construct knowledge through collaboration with others. Vygotsky introduced the concept of the zone of proximal development (ZPD), which refers to the difference between what a learner can do independently and what they can achieve with guidance and support from a more knowledgeable other, such as a teacher or peer.

Constructivist learning theories emphasize the importance of hands-on experiences, where learners actively engage with materials and manipulate objects to build their understanding. This aligns with the principles of experiential learning proposed by David Kolb, who suggested that learning occurs through a cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Flipped classrooms provide opportunities for students to engage in hands-on activities, experiments, and simulations, allowing them to construct knowledge through direct experiences.

Furthermore, constructivist theories highlight the significance of interaction with peers in the learning process. Social constructivism, as advocated by theorists like Lev Vygotsky and Jerome Bruner, emphasizes the collaborative nature of learning and the role of dialog, negotiation, and shared meaning-making in knowledge construction. In flipped classrooms, peer interaction is fostered through collaborative activities, group discussions, and peer teaching, enabling students to learn from each other and co-construct knowledge together.

Finally, constructivist learning theories emphasize the importance of reflection on learning. Reflective practice, as proposed by theorists like Donald Schön, involves critically examining one's experiences, assumptions, and actions to enhance learning and professional development. In flipped classrooms, students are encouraged to reflect on their learning experiences, identify misconceptions, and articulate their understanding, fostering metacognitive awareness and self-regulated learning.

3. Benefits of flipped classrooms in mathematics education

Flipped classrooms offer a myriad of advantages over traditional instructional methods, particularly in the context of mathematics education. Below are some key benefits:

3.1 Improved student engagement and participation

Flipped classrooms transform passive learning into an active, engaging experience [8]. By encountering foundational material outside of class through pre-recorded lectures, interactive tutorials, or assigned readings, students arrive in the classroom primed and ready to participate actively in discussions and problem-solving activities. This proactive engagement not only enhances comprehension but also cultivates a collaborative learning environment where students feel empowered to share ideas, ask questions, and explore mathematical concepts in depth. As a result, classroom interactions become dynamic exchanges of knowledge, fostering a sense of community and intellectual curiosity among students.

3.2 Enhanced conceptual understanding and problem-solving skills

The flipped classroom model places a strong emphasis on application and problem-solving, enabling students to deepen their conceptual understanding of mathematical principles [5]. By dedicating in-class time to hands-on activities, group work, and guided practice sessions, students have the opportunity to apply theoretical knowledge to practical situations, analyze complex problems, and develop innovative solutions collaboratively. This active exploration not only reinforces learning but also fosters critical thinking, analytical reasoning, and resilience in the face of challenges. Moreover, by grappling with authentic mathematical problems, students gain a deeper appreciation for the relevance and applicability of mathematical concepts in real-world contexts, preparing them for success in academic and professional endeavors.

3.3 Personalized learning experiences

Flipped classrooms offer unparalleled flexibility, allowing students to engage with course material at their own pace and according to their individual learning preferences [10]. Through asynchronous access to pre-class materials, students can review content multiple times, pause to take notes, and seek clarification on challenging topics as needed. This self-directed learning promotes autonomy and self-regulation, empowering students to take ownership of their education and pursue deeper understanding beyond the confines of traditional instruction. Furthermore, instructors can leverage data analytics and formative assessments to tailor instruction to the unique needs and learning styles of each student, providing targeted support and scaffolding to maximize learning outcomes. This personalized approach not only accommodates diverse learners but also fosters a culture of inclusivity and accessibility in mathematics education.

3.4 Facilitation of active learning and student-centered instruction

Flipped classrooms embody the principles of active learning and student-centered instruction, fostering an environment where students are active participants in the learning process [11]. In-class activities are designed to promote collaboration, critical thinking, and problem-solving, challenging students to construct knowledge collaboratively and apply mathematical concepts in authentic contexts. Through peer-to-peer interaction, collaborative problem-solving, and peer teaching, students develop communication skills, teamwork, and metacognitive awareness, preparing them for success in an increasingly interconnected and dynamic world. Moreover, by engaging with diverse perspectives and approaches, students gain a deeper appreciation for the richness and complexity of mathematical thinking, transcending rote memorization and fostering a lifelong love of learning.

4. Implementation strategies in mathematics education

Implementing flipped classrooms effectively in mathematics education requires tailored strategies to address the unique challenges and opportunities of the discipline. Below are key strategies for successful implementation:

4.1 Designing pre-class materials: selecting resources and creating engaging content

In mathematics education, pre-class materials should aim to provide clear explanations of mathematical concepts and offer opportunities for students to practice problem-solving independently [3, 12]. Educators can select resources, such as instructional videos, online tutorials, interactive simulations, or practice exercises that align with the curriculum and cater to different learning styles. To enhance engagement, educators can incorporate real-world examples, visualizations, and interactive elements that demonstrate the practical applications of mathematical concepts. For instance, in algebra, videos could visually represent solving equations or graphing functions, while in geometry, interactive simulations could illustrate geometric transformations or the properties of geometric shapes. Additionally, providing guided practice problems with step-by-step solutions helps students build confidence and reinforce understanding before engaging in collaborative activities during class.

4.2 Utilizing technology platforms for content delivery and student interaction

Technology platforms play a crucial role in delivering pre-class materials and facilitating student interaction in mathematics education. Educators can utilize learning management systems (LMS), online math platforms, graphing software, and interactive whiteboards to deliver content, assign practice problems, and provide feedback to students [3, 12, 13]. For example, online math platforms can offer adaptive practice exercises tailored to individual student needs, allowing students to receive targeted practice and immediate feedback on their progress. Virtual whiteboards and collaborative document sharing tools enable students to work together on problem-solving tasks, share mathematical reasoning, and collaborate in real time. Moreover, interactive simulations and dynamic graphing software provide students with opportunities to explore mathematical concepts visually, experiment with parameters, and develop intuition about mathematical relationships.

4.3 Incorporating formative assessment and feedback mechanisms

Formative assessment is integral to monitoring student progress and providing targeted support in mathematics education. Educators can incorporate formative assessment strategies, such as online quizzes, concept checks, peer evaluations, and self-assessment tools to gauge student understanding and identify areas for improvement [14]. For example, online quizzes can assess students' procedural fluency and conceptual understanding of mathematical concepts, while concept checks can probe students' understanding of key mathematical principles and connections. Peer evaluations and collaborative problem-solving tasks encourage students to explain their reasoning, justify their solutions, and engage in productive mathematical discourse. Providing timely and specific feedback on students' problem-solving approaches and mathematical reasoning helps guide their learning journey and address misconceptions effectively. Moreover, encouraging students to reflect on their problem-solving strategies and revise their solutions fosters metacognitive awareness and promotes deeper learning in mathematics.

4.4 Addressing challenges such as access to technology and student resistance

In mathematics education, ensuring equitable access to technology resources is essential for the success of flipped classrooms [15]. Educators should proactively address challenges related to access by providing alternative formats for pre-class materials, offering offline resources, and facilitating access to technology resources through school or community resources. Moreover, addressing student resistance to flipped instruction requires clear communication of the benefits of active learning, providing support and guidance in navigating online resources, and fostering a supportive learning environment where students feel empowered to take ownership of their learning. Educators can model effective use of technology tools, provide opportunities for peer collaboration and peer support, and offer scaffolding and differentiation to meet the diverse needs of students. By addressing challenges proactively and promoting a culture of collaboration and resilience, educators can create a conducive learning environment where all students can thrive in mathematics education.

5. Case studies in mathematics education

Case studies provide valuable insights into the implementation of flipped classrooms in mathematics education, highlighting successful practices, challenges encountered, and lessons learned. Studies investigating flipped classroom implementation have been conducted in all levels of education. However, we tended to present a systematic review of only studies carried out in determining the effectiveness of flipped classrooms in enhancing mathematics among secondary school learners. **Table 1** below shows a summary of reviewed studies conducted in mathematics education on the effectiveness of the flipped classroom approach.

In this review, the search strategy involved using the terms "flip" or "invert" in proximity to "class" or "instruct" or "learn" or "teach" or "subject" within three words of each other. These were then combined with keywords representing various school contexts: secondary, "high school," "middle school," K12", and "K-12". This approach included broad terms such as "flipped classroom", "flipped learning," and "inverted instruction," as well as more specific phrases like "flipping a mathematics classroom" and "flipping an elementary science subject."

We searched three electronic databases: Web of Science, Scopus, and Education Research Complete. Web of Science and Scopus were chosen for their broad peer-reviewed literature coverage, including social sciences, while Education Research

S/N	References	Context/ level/grade	Focus of study/math content/country	Methodology	Activities used in classroom/outside classroom (Duration)	Findings	Challenges experienced (positive and negatives)
1	[16]	High School/ Grade 11	Effects of FC on student performance, attitude, and engagement in Algebra 2 in the USA.	Quantitative (quasi-experimental study) Test statistics used: t-test	Watching pre-recorded lecture videos, group discussions, Practical work (6-week duration).	FC was effective in increasing students' attitude and engagement level.	Some participants in the experimental group who skipped the instructional videos could not fully engage in the learning activities. Low motivation on students' part.
2	[17]	High School/ Grade 9	Examine the effectiveness of the flipped classroom on students' achievement and motivation in trigonometry in Taiwan.	Quantitative (quasi-experimental design) Test statistics used: ANCOVA, t-test and MONOVA	Lecture and discussion, problem solving, homework, pre-recorded video lessons, activities based on video lessons, group discussion, face-to-face support (4-week duration).	Findings showed that students in the FC had significantly higher achievement and motivation.	Due to time constraints, students could not ask questions while watching lesson videos. Interactive video lessons are recommended to enhance learning in the FC.
3	[3]	Secondary School/SSS 2	Effect of FC on students' achievement and interest in Circle Geometry in Nigeria	Quantitative (quasi-experimental study) Test statistics used: ANCOVA	Group discussions, online blogs, videos, flashcards, worksheets, online quizzes (4-week duration).	FC was effective in enhancing students' achievement and interest in geometry.	Unequal access and lack of technology among some students in the experimental group posed some challenges during out-of-class activities.
4	[18]	High School/ Grade 9	Effects of the flipped model of instruction on student engagement and performance in Algebra 1 in the USA	Mixed method design Test statistics used: t-test and Thematic analysis	watching videos, listening to podcasts, reading articles, viewing presentations, homework content notes, hands-on activities, participated in real-world applications (7-week duration).	Students experienced increased engagement and communication with the FC model, though no significant differences were found compared to traditional classroom teaching.	Limited time frame of the project. Use of technology helped improve students' engagement and performance in the flipped classroom even though some students resisted.

S/N	References	Context/ level/grade	Focus of study/math content/country	Methodology	Activities used in classroom/outside classroom (Duration)	Findings	Challenges experienced (positive and negatives)
5	[19]	High school/ Grade 8	Examined the academic performance and perceptions of secondary English Language Learners in an Algebra 1, comparing flipped instruction to traditional instruction at a high school in the USA	Quantitative test statistics used: t-test	Students used instructional videos, iPads, and graphing calculators. They received direct instruction at the beginning of class, completed computer-based assignments, participated in group problem-based learning activities, and took quizzes and monthly tests. Videos were watched outside class or before/after class, and Blendspace was utilized (Duration: academic year).	Findings indicate students in the flipped course enjoyed it more and performed slightly better than those in traditional instruction, but the performance difference was not statistically significant.	Organizing the chunk of videos into segments posed some challenges. There was no accountability for students watching videos outside of class and no ongoing instructional feedback during flipped teaching.
6	[20]	Secondary School/ Grade 12	Impact of FC on underperforming and high ability students in Coordinate Geometry in Hong Kong	Mixed method (experiential design) Test statistics used: t-test and Thematic analysis	Small-group learning activities, peer interaction, video lectures, real-world problems, quizzes online, revision videos online (6-week duration).	Results revealed that the FC can enhance mathematics achievement for both underperforming and high-ability students.	It is difficult to satisfy all students due to the time constraints. Some students might complete the online quizzes casually. Questions could not be asked immediately while watching videos.
7	[21]	Secondary school/Grade 12	To determine how teachers can design and implement FC to benefit mathematics learners in Coordinate Geometry in Hong Kong.	Mixed Method Test statistics used: Mann-Whitney U test, t-test and Thematic analysis	Videos instruction, problem solving, online exercises, group discussion/ work, real-life problems, reviewing out-of-class learning and clarifying their misunderstandings (6-week duration).	Results showed that student achievement levels in mathematics improved in the flipped classroom compared to the non-flipped classroom.	The considerable start-up efforts required of teachers and the students' lack of pre-class motivation were challenges. However, students are now more likely to ask questions. Another challenge is increased teachers' workload.

S/N	References	Context/level/grade	Focus of study/math content/country	Methodology	Activities used in classroom/outside classroom (Duration)	Findings	Challenges experienced (positive and negatives)
8	[22]	High School/ Grade 10	To investigate the impact of FC-enhanced blended learning environments on students' cognitive learning outcomes, as well as students' satisfaction and self-determination for their algebra learning in Greece.	Quantitative (Quasi-experimental design) Test statistics used: ANCOVA and t-test	Moodle Learning Management System was developed. Activities used included problem-based and project-based approaches, the Jigsaw technique, Think-Pair-Share, and brainstorming. Students engaged in collaborative projects, hands-on activities, homework, pre-session tasks hosted on Moodle, educational videos, and online quizzes (3-month duration).	The results showed that the FC significantly improved students' cognitive learning outcomes and satisfaction levels. Students in the FC reported higher fulfillment of self-determination needs, with low-performing students showing the greatest gains in all self-determination dimensions.	Nil

Table 1.
Summary of reviewed studies on effectiveness of flipped classroom (FC) approach.

Complete focuses exclusively on leading educational research. Our criteria aimed to understand the implementation, challenges, and effectiveness of flipped classrooms in secondary mathematics education. Included studies had to be empirical, focus on secondary or high school levels, report on the effectiveness of flipped classrooms in math, describe pre-class and in-class activities, and detail the implementation strategies and technologies. Only peer-reviewed studies published in English were considered.

The search terms yielded 28 journal articles from three databases published between 2015 and 2024. Following PRISMA guidelines [23], 28 articles were screened by titles and abstracts. Seventeen articles were excluded for not meeting the criteria, often due to irrelevance or non-secondary school contexts. Eleven full-text articles were then assessed, with three more excluded for lacking clear flipped classroom implementation details. Ultimately, eight articles were reviewed. **Figure 1** shows the overall selection process for the review. Key data extracted included author(s), title, year, location, methodology, study focus, participants, duration, flipped classroom strategies (pre-class and in-class), technologies used, major findings, and challenges.

5.1 General description of reviewed studies

The eight journal articles included in this review encompass research conducted at both junior high and senior high school levels. Geographically, the studies span multiple regions: three were conducted in the United States of America (USA), one in Taiwan, one in Nigeria, two in Hong Kong, and one in Greece. The mathematical content areas covered by these studies include algebra, trigonometry, and geometry. A significant portion of the studies focused on examining the effectiveness of the

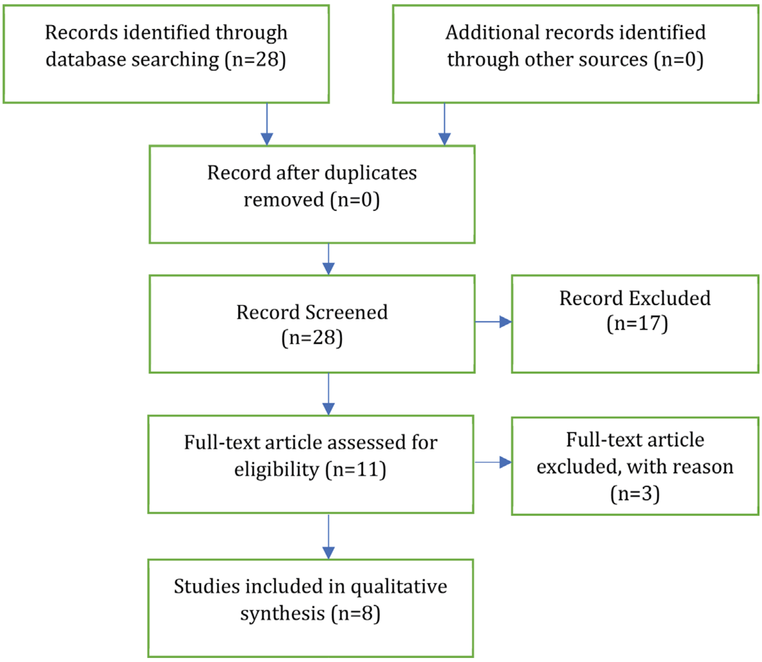

Figure 1.
Article selection process (Adapted from Ref. [23]).

flipped classroom (FC) model in enhancing various educational outcomes such as students' performance, attitude, and engagement. Specifically, Bergeson [16], Clark [18], and Graziano and Hall [19] investigated these aspects. Additionally, Bhagat et al. [17] and Egara and Mosimege [3] explored the impact of FC on students' achievement, interest, and motivation. Two studies, Lo and Hew [20] and Lo et al. [21], delved into the implementation of the flipped classroom model for both underperforming and high-ability students, emphasizing its integration with a standard instructional design model. Finally, Sergis et al. [22] examined the effects of FC-enhanced blended learning environments on students' cognitive learning outcomes, satisfaction, and self-determination.

5.2 Flipped classroom implementation of reviewed studies

The reviewed studies implemented the flipped classroom model by engaging students in pre-class activities to prepare for in-class learning. These pre-class activities included watching instructional videos, taking online tests, note-taking, engaging with additional learning materials, and participating in reflections and discussions. Video watching was a common element across all studies, serving to deliver content and demonstrate necessary procedures for hands-on activities. In-class activities varied but generally focused on student-centered approaches. Group activities were predominant, allowing students to discuss concepts and collaborate on tasks [3, 18]. Other in-class activities included individual assessments, question and answer sessions, teacher-assisted instruction, quizzes, and direct instruction when needed [17, 19, 22]. The varied implementation strategies reflect the flexible nature of the FC model, which involves content delivery before class and active learning during class, adapting to different educational contexts and student needs.

5.3 Challenges encountered with flipped classroom of reviewed studies

Studies investigating students' and teachers' perceptions of flipped classrooms revealed several challenges. The primary issues included students' motivation and accountability, increased teacher workload, limited time, student resistance due to unfamiliarity, and access to technology. A common problem was students' lack of motivation to engage in pre-class activities and their inadequate preparation for in-class learning. Teachers struggled to monitor and verify students' participation, with [20] noting difficulties in ensuring genuine engagement. Teachers reported a significant increase in workload due to the time and effort required to prepare instructional videos, often needing to learn new technical skills. Time constraints affected both preparation and student engagement with pre-class materials. Student resistance to the unfamiliar flipped classroom approach further complicated implementation. Ensuring all students had access to the necessary technology for pre-class activities was also a significant hurdle, impacting the model's overall effectiveness.

5.4 Effectiveness of the flipped classroom approach of reviewed studies

The effectiveness of the flipped classroom in mathematics instruction was examined using various research designs across the reviewed studies. Most studies employed quasi-experimental designs, comparing flipped classrooms with traditional lecture-based classrooms. The majority of the studies reported that flipped classrooms significantly increased students' learning achievement, participation, and learning attitudes. For instance, Bhagat et al. [17] found that the flipped classroom was more effective than traditional classrooms in enhancing student motivation and achievement in trigonometry. However, some studies showed mixed results. Graziano and Hall [19] reported that while students in flipped classrooms enjoyed the learning process more, the performance difference compared to traditional classrooms was not statistically significant. Similarly, Clark [18] found no significant differences in student performance between flipped classrooms and traditional classrooms, though flipped classrooms did increase student engagement. Overall, while the majority of studies employing quasi-experimental designs concluded that flipped classrooms were more effective than traditional classrooms, there were inconsistencies as few studies reported similar results for both instructional methods.

5.5 Lessons learned and recommendations

This review provides insights into flipped classroom research in mathematics education, indicating that flipped classrooms generally enhance students' learning achievement, motivation, and engagement compared to traditional methods. However, some studies report no significant differences, highlighting inconsistencies in the findings. Research reveals that teachers use a variety of pre-class and in-class activities and technologies, showing diverse and effective implementation strategies. Common themes in successful implementations include clear communication of expectations, providing scaffolding and support for students as they navigate pre-class materials, and fostering a collaborative learning environment.

Despite the benefits, significant challenges exist, including issues with student motivation and accountability, increased teacher workload, limited time, student resistance, and access to technology. Addressing these challenges could improve future implementations of flipped classrooms. Educators should continually assess and adjust their practices based on student feedback, monitor student progress, and provide timely support and intervention as needed. By leveraging technology effectively, fostering active learning, and promoting student engagement, educators can create transformative learning experiences that empower students to succeed in mathematics and beyond. While most studies found that flipped classrooms improve student performance and motivation, some reported no significant difference compared to traditional classrooms. These mixed results underscore the need for ongoing research and refinement to fully realize the potential benefits of flipped classrooms in mathematics education.

6. Conclusion

In conclusion, flipped classrooms offer a promising approach to mathematics education, presenting both benefits and challenges for educators and students alike. Throughout this chapter, we have explored the potential of flipped classroom methodologies to transform traditional teaching paradigms and enhance learning outcomes in mathematics education. Flipped classrooms have demonstrated several benefits, including increased student engagement, enhanced conceptual understanding, and personalized learning experiences. By leveraging technology and active learning strategies, flipped classrooms promote collaboration, critical thinking, and problem-solving skills among students. However, challenges such as technology accessibility, student motivation, and effective implementation strategies must be addressed to maximize the effectiveness of flipped classroom approaches.

Key insights from this chapter include the importance of aligning flipped classroom activities with learning objectives, fostering student motivation and accountability, and evaluating the success of flipped classroom approaches through ongoing assessment and reflection. Educators are encouraged to design engaging pre-class materials, provide scaffolding and support for students, and leverage adaptive learning technologies to personalize instruction and support diverse learners in mathematics education. Innovative teaching approaches, such as flipped classrooms, play a crucial role in shaping the future of STEM education by preparing students with the critical thinking, problem-solving, and digital literacy skills needed to succeed in the twenty-first-century workforce. By embracing innovative pedagogies, educators can create dynamic and interactive learning environments that inspire curiosity, creativity, and lifelong learning in students. As we continue to explore new horizons in mathematics education, let us embrace the opportunities presented by flipped classrooms and other innovative teaching approaches to empower the next generation of STEM leaders and innovators.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

STEM Skills in the Development of Modeling Projects: The Stray Animal Growth Model

Jeannette Galleguillos

Abstract

Modeling projects are a pedagogical strategy involving learners working in small groups to propose a problem based on a topic of their interest and solve it using mathematics. As a part of a course focusing on this pedagogical approach, a group of prospective teachers focused on modeling the growth of stray cats and dogs. The aim of this study was to identify the tensions that the group encountered during the development of their project and to identify the learning opportunities that emerged during this process. The results reveal tensions in the modeling process due to difficulties with the mathematics involved in solving the problem. To address these challenges, the group simplified the variables in the original problem and developed an exponential model to reflect the growth of stray dogs and cats. Throughout the process, the group developed STEM skills to address a real problem and solve it mathematically. Moreover, the project generated important reflections on responsible pet ownership.

Keywords: modeling projects, teacher's education, problem posing, activity theory, exponential model

1. Introduction

The present study addresses the modeling project strategy outlined by Borba and Villarreal [1], in which prospective mathematics teachers, working in small groups, propose a problem based on a topic of their interest and develop it with the help of the teacher and digital technologies. Using this strategy, it is possible to establish solid connections between mathematics and the real world. In the development of projects aimed at promoting knowledge and skill acquisition, learners are asked to propose a question or a problem based on a real-life situation they deem relevant [2], which should contrast with typical textbook problems that can be solved using classic procedures. The development of a project with these characteristics requires advanced knowledge and information that can be obtained through Internet searches and with the support of the teacher.

According to the current STEM goals, individuals are required to develop knowledge, attitudes, and skills to identify real-world problems and to apply interdisciplinary knowledge and skills to shape their own learning experience [3]. To achieve STEM goals in K – 12 education [4], it is essential that teachers are empowered with real-world learning experiences and problems. To this end, a modeling project strategy was adopted in this study, focusing on an actual project implemented as a part of a course taken by prospective mathematics teachers.

Regarding the implementation of modeling in the teaching and learning process, Schukajlow and Blum [5] recognise two broad categories in the pertinent literature, an instruction-oriented approach along behaviourist lines and a constructivist-oriented approach, which may comprise enquiry learning and problem posing. In both cases, teacher preparation is required that goes beyond merely observing how students solve problems. The authors thus highlight the need for instructional principles of self-regulation in problem-solving, including providing students with opportunities to engage in social learning by encouraging peer and small group discussions, as well as teaching students how to use problem-solving strategies. In the same vein, the modeling project strategy offers opportunities for the learners to be actively involved in the modeling process while working collaboratively with their peers and the teacher, and utilising relevant online resources.

One of the difficulties in implementing modeling projects is that some learners may not know how to proceed with their execution [6], so they are overly dependent on the teacher to advance at each step. To address this issue, in this study, a support guide based on [7, 8] was used to assist prospective teachers in advancing the project. The aim of the support guide is to prompt the group working on the project to focus on its topic, question or problem, and then proceed to the mathematisation, explanation and reflections or conclusions. In this work, we see the difficulties of preservice teachers as tensions, and learning opportunities as possibilities for expansion from the perspective of expansive learning [9]. Accordingly, the aim of this study is to identify the tensions within a group of prospective teachers in the development of their project and to study the learning opportunities that the group experienced in this process.

2. Theoretical framework

2.1 Modeling projects

We understand mathematical modeling as any relation between mathematics and the real world (e.g., [10]), being a process that goes from the real world to mathematics. During this process, the concepts of simplifying and mathematising are used as a part of the modeling cycle [11]. According to Blum and Leiß [11], the real situation has to be simplified, structured and made more precise, leading to a real model of the situation, while mathematisation corresponds to the transformation of this initial model into a mathematical model, i.e., “its data, concepts, relations, conditions and assumptions are to be translated into mathematics” [10].

There are different ways of viewing modeling. Particularly, in the modeling project approach of Borba and Villarreal [1], learners work in small groups and choose a topic of their interest to investigate. Once the project topic is determined, they pose a question or a problem that can be solved using mathematics. This strategy allows learners to make connections between mathematics and reality, helping them appreciate the practical utility of mathematics. Moreover, learners may feel encouraged to engage in mathematical modeling because they have the opportunity to work on a topic of personal interest. For this type of strategy to be successful in school mathematics education, (prospective) teachers must develop the skills required to work with projects and to guide their students.

Other studies on modeling and projects involving (prospective) teachers have been published, referring to prospective teachers' experience of modeling with the use of technologies [12], teachers' dilemmas and conflicts when they propose a modeling problem [13], prospective teachers using modeling as an evaluation strategy [14] and modeling through the design of task for teachers [15].

The modeling skills emphasised by the Chilean education system require the teacher to consider using, applying, selecting, comparing and evaluating models, focusing on the objectives to be achieved at grade levels 1–10 [16], along with building models of real situations, required at grade levels 11 and 12 [17]. However, most of the activities proposed in didactical books on modeling correspond to the applications and use of models rather than model development.

Thus, by involving prospective teachers in investigating a topic of interest under a modeling project, they are encouraged to participate in the modeling activity and to adopt a strategy that breaks away from a behavioural approach. In addition, the modeling project strategy can be approached in a way that uses mathematics familiar to students as well as learning new mathematical knowledge, adding multiple skills to pose a problem and solve it using technologies [1]. Considering the challenges for teachers to integrate modeling (and projects) into the teaching and learning process, in a socio-cultural manner [18], this study used an activity theory perspective to understand the experience of a group of prospective teachers in the modeling process.

2.2 Activity theory

The cultural-historical theory of activity, also known as activity theory, was established from the studies conducted by Vygotsky [19], Leontiev [20] and later Engeström [9], among other authors. Vygotsky essentially studied the development of human thought, contributing to the development of the notion of mediation, in which subject–object relations are mediated by artefacts. In a broader sense of the notion of mediation in learning, it is established that learning occurs in a dialectical process, in which the subject is transformed by the world, and, in turn, the world is transformed by the subject.

According to the activity theory, people actively participating in joint activities to solve problems are subjects in an activity system [9]. On the other hand, the object is considered the real purpose of the activity system (e.g., to solve a certain problem). Artefacts correspond to the means that subjects use to achieve their object [9]. In the interaction of the subjects in the activity system, different perspectives on how to solve their problem (reach their object) may arise. These different opinions are expressed through words or gestures. Generally, opposing ways of approaching a situation collide with each other and reflect the existence of internal contradictions in the system. This indicates that internal contradictions are the cause of the tensions. The contradictions are not easily perceived, but can be identified by analysing people's words or gestures [21]. In this work, we view tensions as manifestations of contradictions [21]. Learning by expanding [9] corresponds to the emergence of tensions and their successful resolution, leading the subjects to the construction of a new system that offers a solution to the initial problem. The resolution of contradictions is an indication of learning or progress in the system.

3. Methods

This study was developed under the parameters of *basic qualitative* research [22], in which a phenomenon is studied through the experiences reported by the subjects who were involved in that phenomenon. The aim was to identify tensions encountered by prospective teachers who worked as a group on a modeling project as part of an activity included in a mathematical modeling course offered in the context of an initial education course for mathematics teachers at a Chilean university. The course is integrated into the curriculum in the seventh semester (out of a total of ten), being a compulsory course with three hours of classes per week. The project at the focus of this investigation was developed in 2021, and students were given 1 month for its implementation, but due to the restrictions imposed by the Covid-19 pandemic, work was conducted online.

Six prospective teachers took part in the course, and by the time the project was initiated, they had already worked on modeling linear and exponential problems and were also asked to propose modeling problems related to school mathematics at grade levels 7–12. They were then given examples of modeling projects as a preparation for using the modeling project strategy. Thus, prospective teachers were asked to form two-member groups based on their own affinity, according to Borba and Villarreal [1], and in coherence with Schukajlow and Blum [5]. The resulting three groups were asked to choose a relevant topic to investigate and propose a problem. They chose topics related to the environment, bees and animal care. In this work, focus is given to the animal care project designed by a group of two prospective teachers, Anne and Martin (fictitious names). In accordance with the activity theory framework [9] and the modeling project strategy [1], the project was developed by the group in collaboration with the course teacher while using digital technologies.

The instruments used in this study include a project report document, a short video presentation of the project, and a narrative written by the group about the experience of developing a modeling project. The document contains information about the project, such as topic and information found on the Internet, problem or question, mathematising, explanations and reflections or conclusions. The group presented their work in an 8-minute video summarising the project. A narrative was written by Martin but expressed the experience of both members of the group. The narrative was guided by the following prompts: What was your experience developing a modeling project like? How was the idea of the theme born? What modeling stages do you consider you experienced and which ones you did not utilise?

As the group chose animal care as their project topic, they proposed modeling the growth of stray dogs and cats, which is a prominent issue in Chile and generated reflections that allow us to confront this form of animal mistreatment. The analyses presented in the following sections focus on detecting the tensions of the group participants in developing their project through qualitative analysis of the narrative. Another aim was to identify possible developmental (or learning) opportunities in the modeling process. Thus, from Engeström's perspective on activity theory, the purpose is to evidence the occurrence of expansive learning [9] in the group, i.e., to visualise tensions and contradictions in the development of their project, as well as to observe whether the group was able to resolve the tensions by developing a model that solves their problem [23].

4. Analysis and results

4.1 Reporting on the project

The project was described in the report document and in the video following the steps based on the supporting guidance [7]: project topic, problem or question, mathematisation and reflections. Some images of the video presentation of Anne and Martin are shown in **Figure 1**.

4.1.1 Project topic

The group was interested in caring for animals and improving the conditions of those who are abandoned and suffer from diseases, hunger and thirst. As explained by Anne, their topic was "Rescue and sterilisation of stray animals"—particularly dogs and cats—and combining the data provided by the organisation "Stray animals without voice" with the information available on the Internet to analyse and model the problem.

4.1.2 Problem or question

The group formulated the problem as follows:

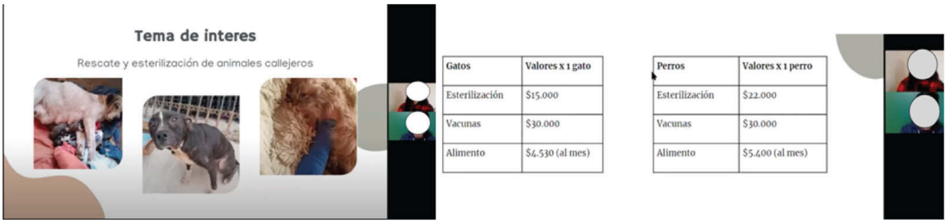
If stray animals are not rescued or sterilised, their population will increase. In 2020, 343,000 abandoned animals were registered in Chile, 88,000 of which were cats and 255,000 were dogs.

Accordingly, they posed the following questions to aid them in their modeling task:

1. If in 2021 121,440 cats and 323,850 dogs were registered, what is the percentage of growth in cats? What is the percentage of growth in dogs? What will the number of stray animals be in 2025?

2. The organisation "Stray animals without voice" on average rescues 32 animals per month to reduce overpopulation and improve their quality of life. Thus, they must pay for vaccines and food, with the following costs (see **Tables 1** and **2**).

With the data provided above, what would be the annual expense assuming that 12 cats and 20 dogs are brought to the facility each month?



Tema de interes

Rescate y esterilización de animales callejeros

Gatos	Valores x 1 gato
Esterilización	$15.000
Vacunas	$30.000
Alimento	$4.530 (al mes)

Perros	Valores x 1 perro
Esterilización	$22.000
Vacunas	$30.000
Alimento	$5.400 (al mes)

Figure 1.
Images of video presentation.

Cats	Expenses per cat (in Chilean currency)
Sterilisation	$ 15,000
Vaccines	$ 30.000
Food	$ 4,530 (per month)

Table 1.
Expenses per cat.

Dogs	Expenses per dog (in Chilean currency)
Sterilisation	$ 22,000
Vaccines	$ 30,000
Food	$ 5,400 (per month)

Table 2.
Expenses per dog.

4.1.3 Mathematisation

Using the data for 2020 and 2021, the group found 38% growth in stray cats and a 27% growth in stray dogs, thus answering the first part of Question 1. Then, with some interactions with the teacher of the course, they projected the growth in these populations by 2025, assuming that animals are not sterilised (**Tables 3** and **4**), finding the exponential function for both cats and dogs.

From this, the group established the exponential growth functions—Eqs. (1) and (2)—which were explained by Martin in the video:

$$f(x) = 88{,}000 \cdot (1.38)^x \tag{1}$$

where f represents the annual growth in the cat population, and

$$g(x) = 255{,}000 \cdot (1.27)^x \tag{2}$$

where g represents the annual growth in the dog population.

Year	Growth in the number of stray cats: $f(x)$
0	88,000
1	$88{,}000 \cdot (1 + 0.38)$
2	$88{,}000 \cdot (1 + 0.38)^2$
3	$88{,}000 \cdot (1 + 0.38)^3$
…	…
n	$88{,}000 \cdot (1 + 0.38)^n$

Table 3.
Growth in stray cat population.

Year	**Growth in the number of stray dogs:** $g(x)$
0	255,000
1	$255{,}000 \cdot (1 + 0.27)$
2	$255{,}000 \cdot (1 + 0.27)^2$
3	$255{,}000 \cdot (1 + 0.27)^3$
…	…
n	$255{,}000 \cdot (1 + 0.27)^n$

Table 4.
Growth in stray dog population.

It was projected that, under the conditions of the proposed problem, in 2025 there will be 440,431 abandoned cats and 842,478 abandoned dogs, totalling 1,282,909 stray animals. Then, they represented both graphs, observing how these populations would increase in that period (**Figure 2**). They also calculated the costs of sterilisation, vaccines and food to support the stray animals, which are not reported in this work.

4.1.4 Reflection

In the video Anne shared the group's reflections, commenting on the rampant growth of stray animals, stressing the importance of caring for stray animals and emphasising responsible ownership and care of pets.

4.2 Tensions and learning opportunities

The following excerpts are taken from the group's narrative written by Martin:

> *(…) Mathematising the project involved a lot of work, since, when the problem was posed, we were not clear about the mathematics that should be used to model the growth of the population of these stray animals, since at the beginning we wanted to*

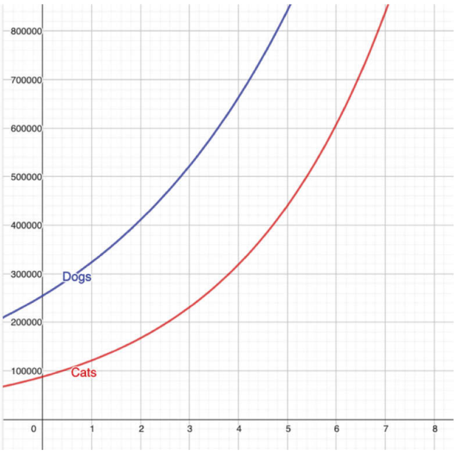


Figure 2.
Exponential growth in the population of abandoned pets.

> *have different factors to make the model, such as birth rate, mortality, abandonment and annual rescue, as well as the medical price of sterilisation. For this reason, it was not possible to find the mathematics that would fit all the factors that we wanted to take into account, so we had to focus on one variable, which we believed to be the most important, which was the annual birth rate.*
>
> *(…) Throughout this process, we were able to identify the problem we wanted to work on, in a real-life context, and it was also a problem of social relevance, which generated even greater interest. After researching all this data, we were able to mathematise the problem and this led to the creation of the relevant model, which allowed us to make a synthesis of the problem, returning to real life, raising awareness of the problem of pet abandonment and what the disproportionate growth would be like if the animals were not sterilised.*

In the process of constructing a modeling project, tensions as well as learning opportunities were experienced by the participants. First, the narrative shows that when the initial problem was posed, the group was not clear about the mathematics to be used to model the growth of stray animals due to the fact that too many variables were considered in the problem. Thus, tension was generated by the contradiction of posing a problem based on reality but not knowing how to solve it (part 1 of the problem). Moreover, the prospective teachers were expected to be able to propose problems that could be solved using the mathematics at grade levels 7–12.

The group pointed out that, in order to resolve the contradictory situation, it was necessary to make a decision regarding the variables to be addressed in the problem, which from the notions of modeling is understood as simplifying the problem. Thus, they considered only the variable "annual birth rate of the animals," as evident from the following comment: "For this reason, it was not possible to find a mathematics that would fit all the factors that we wanted to take into account, so we had to focus on one variable, which we believed to be the most important, which was the annual birth rate." These assertions reveal both the contradiction and the decision to choose the most influential variable that allowed the group to refine the problem and answer the question. In this way, the prospective teachers resolved the contradiction by varying the problem statement and simplifying it, so that it was based on a single variable; thus, an expansive learning process took place [9].

The results also reflect the development of STEM skills in prospective teachers, since during the process Anne and Martin were able to identify a socially relevant problem taken from the context of their country, with real data taken from the Internet, and construct a problem related to a relevant topic. This is reflected in the following statement: "Throughout this process, we were able to identify the problem we wanted to work on, in a real-life context, where it was also a problem of social relevance, which generated even greater interest. After researching all this data, we were able to mathematise the problem and this led to the creation of the relevant model, which allowed us to make a synthesis of the problem, returning to real life." They further indicated that developing a problem pertaining to their chosen topic generated greater interest in the modeling process.

The project addresses the problem of pet abandonment in Chilean society and can be presented or developed in schools to generate deep reflections on this issue, which can lead to social transformation. The group pointed out that they chose this particular project as a way to raise awareness of the problem of pet abandonment and lack of sterilisation in Chile. In addition, the project presents an opportunity to enhance mathematical knowledge by using percentage calculations and finding patterns.

As the project objectives were achieved, the contradiction situation was resolved, which implies that expansive learning took place [23], as reflected in the group's approach to a real problem that could be solved with school-level mathematics while bringing focus to the problem of animal abandonment in the streets. The learning opportunities resulting from this project include skills to identify a problem of social relevance, constructing a problem and solving it using mathematics and the Internet (all of which are vital STEM skills), as well as reflections that prompt the school community to face social problems and respect animals.

5. Conclusions

The study results show that a contradiction emerged in posing a real-life problem that has too many variables and is thus outside the scope of school knowledge. The contradiction was resolved by taking the decision to choose the most important variable for the problem, and simplifying it, which corresponds to expansion. The implementation of modeling projects, in which the learners propose the problem, showed most strongly the need for simplifying the situation.

Second, the results show a greater interest in engaging in modeling situations when the topic has social and cultural relevance, concurring with the findings of other authors [1, 8].

Third, the Internet was a crucial resource for obtaining information on the topic as well as accurate data to propose the problem, acting as an active component in an activity system [24, 25]. The large amount of information led the group to consider all pertinent variables, which resulted in a contradiction (formulating a problem which they cannot solve with school-level mathematics). The resolution of the contradiction goes hand in hand with the decision to choose the most useful and necessary variable to consider in the problem statement, with a focus on knowledge that can be addressed in the school environment and in their future teaching work.

The activity of posing a real-world problem and solving it using the Internet and mathematics led to the enhancement of crucial STEM skills, showing that expansive learning took place [9]. In addition, very important reflections were made on a social problem in Chile, where pets are regularly found abandoned in squares and streets without scruples and despite the municipal efforts and the organisation of care for stray animals for feeding, sterilisation and adoption. It is therefore, a social problem that, based on this situation and the proposed project, can provoke reflections in children and young people in the school environment, addressing socio-critical aspects.

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Chapter 5

Using Educational Robotics (ER) to Promote STEM Problem-Solving in Preservice Teachers

Kamini Jaipal-Jamani

Abstract

With the recent emphasis on learning STEM skills across the k-12 curriculum globally, there is need to provide elementary preservice teachers (PTs) with knowledge of what STEM skills are and how to teach STEM problem-solving skills. In many k-12 curricula, the teaching of STEM skills is mainly incorporated into the science and mathematics curricula. The literature suggests that educational robotics (ER) is an instructional activity that can support school students learn STEM skills. This chapter reports on a study that explored how middle school PTs engaged in STEM problem-solving during a robotics activity. A qualitative, comparative case study design was employed. Data sources included a problem-solving worksheet, audio-recordings of group interactions, and video-recordings or photographs of artifacts. The discourse of six PT groups was analyzed using a STEM problem-solving framework. The results provide insights into the STEM problem-solving decisions of PTs during these ER activities such as PTs drawing on mainly everyday, practical experiences and some basic STEM knowledge to frame and plan the problem, and solving through trial-error-trial feedback loops. Recommendations are made for enhancing PTs STEM problem-solving and the design and implementation of ER activities for elementary students.

Keywords: educational robotics, STEM, problem-solving, preservice teachers, qualitative, comparative case study, collaborative groups

1. Introduction

Rapid technological advancements such as automation and artificial intelligence have made science, technology, engineering, and mathematics (STEM) knowledge and skills an essential requirement of many workplaces [1]. Many countries have introduced STEM into the K-12 curriculum because STEM education is perceived as the foundation that will enable students to enroll in STEM majors at higher education institutions such as universities and enter STEM jobs [2]. However, in some countries, such as in Canada, elementary teachers (primary and middle school) are generalists– they are expected to teach all subjects such as language, science, mathematics and the arts, even though they may not have undergraduate degrees in these subjects. Hence, many elementary teachers in Canada have limited or no university-level academic courses or experiences in many or all the STEM subjects. Consequently, elementary preservice teachers (PTs) have limited knowledge of STEM content and the problem-solving processes used in the STEM disciplines. In this type of teacher education context, it becomes important that elementary PTs, who are expected to teach STEM skills, be introduced to STEM problem-solving activities to develop STEM skills and to learn how to teach STEM in elementary schools.

In Ontario, Canada, the teaching of STEM skills from kindergarten to grade 10 is incorporated into the science and mathematics curricula, respectively. For example, in the Ontario elementary school science curriculum (k-8), science and technology skills are taught through activities that engage students in scientific experimentation, engineering design, and coding; hence the subject is called *Science and Technology* [3]. An instructional activity that promotes the learning of STEM skills is educational robotics [4]. Research studies show that ER supports students' learning of STEM concepts [5, 6], enhances their confidence, interest and participation in STEM fields [7, 8] and helps them develop collaboration and problem-solving skills [9, 10]. The preceding studies emphasize the value of using ER as a STEM learning activity in k-12 settings.

This chapter reports on a study that explored how PTs problem-solved during an ER activity in a *Science and Technology* methods course at a Teacher Education program in Ontario, Canada. Teacher certification in Ontario is divided into three teaching divisions: primary/junior (PJ) which qualifies PTs to teach kindergarten to grade 6; junior/intermediate (JI) which qualifies PTs to teach grades 4–6 and grades 7–10 with a single subject specialty; and intermediate/senior (IS) which qualifies PTs to teach grades 7–10 and grades 11–12 with two subject specialties [11]. The PTs in this study were in the JI teaching division and they participated in an ER learning activity designed to teach grade 8 students how to code and problem-solve. The discourse of six PT groups was analyzed using a STEM problem-solving framework to understand how they problem-solved compared to STEM experts [12]. The findings provide unique insights about the processes PTs used for STEM problem-solving as they learned how to teach STEM with ER. Findings contribute to the literature on ER and elementary PTs STEM problem-solving skills and can also inform the development of course activities for science and technology-related, teacher education methods courses.

2. Literature review

2.1 STEM education, educational robotics and preservice teachers

While there is no single, agreed upon definition of STEM education in the literature [13, 14], the way STEM subjects are organized in most k-12 education systems as discrete subjects around science and mathematics, makes the integration of all four STEM disciplines in K-12 education rare [15]. There is, however, reasonable agreement that STEM education should promote the learning of science, technology, engineering and math knowledge and skills in ways that combine some or all four of the STEM disciplines [16]. As such, STEM education can be conceived of as a teaching approach that integrates knowledge and skills from the STEM disciplines in the same educational experience [13]. Teaching STEM therefore requires that teachers understand what the STEM problem-solving approaches are. Some established problem-solving approaches in the STEM disciplines are scientific inquiry, engineering design, and problem-based learning [17]. Scientific inquiry is characterized by skills such as posing questions about puzzling phenomena and constructing explanations; engineering design is characterized by actions such as defining problems and constructing prototypes of products [18]; and problem-based learning, a more open-based, pedagogical approach, is when students learn by engaging in authentic tasks to solve problems through the processes of problem analysis, self-directed learning, and reporting [19].

Teaching STEM also requires that teachers have some background knowledge of and experiences with ER and basic programming. ER is an educational experience that enables students to work in teams and draw upon STEM knowledge and skills to solve authentic problems [4]. Students interact with concrete manipulatives to construct knowledge therefore ER is an experiential and student-centered learning approach [4, 20]. ER activities are especially suited for developing engineering design skills through problem-based tasks. For example, when students construct and program robots, they define a real-world engineering problem (e.g., how does the robot work to solve the problem), they propose the solution to the problem (e.g., how to build the robot), and they consider optimization (e.g., how to improve the efficiency of the robot to complete the task) [21]. The literature shows that teachers' lack of knowledge and experience with integrated STEM activities such as ER affects elementary students' learning of STEM knowledge and skills [22, 23].

Past research also indicates that PTs gain confidence to teach science when they participate in activities where they learn both the science content and pedagogy in hands-on experiential contexts [24]. For example, recent studies with PTs [25, 26] reveal that participation in ER modules and working collaboratively on problem solving activities with robots resulted in improved knowledge of robots, problem-solving, and how to use robotics for classroom instruction and teaching science. The latter findings suggest that it is important to provide PTs with hands-on, group experiences constructing models and programming with ER to enhance curriculum design and implementation that promotes student learning of STEM knowledge and skills. The study in this chapter is an exemplar of how preservice teachers engaged in collaborative STEM problem-solving with ER as they learned how to teach STEM skills with ER.

2.2 Educational robotics and STEM learning

The adoption of ER into school learning has occurred in various ways over the last 20 years propelled by the development of robotics kits for the masses [5]. Some of the ways ER has been implemented with k-12 students are as after school programs [27, 28] and as robotics competitions [29, 30]. ER experiences can support STEM learning and the development of twenty first century competencies such as critical thinking and innovation (cognitive competencies), communication and collaboration (interpersonal competencies) and initiative and metacognition (intrapersonal competencies [17]. For example, research studies show that ER promotes students' learning of concepts in the STEM areas in both formal and after-school or extracurricular K-12 contexts [5, 31, 32] and develops collaboration and problem-solving skills [9, 10, 33–35]. Since the current study focuses on problem-solving processes in ER contexts, a few salient past studies that focus on problem-solving processes are highlighted.

In the study by [9], the researcher investigated how collaborative behavior among 49 elementary students was developed over 3 years through ER team challenges compared to math problem-solving team tasks. A collaboration assessment rubric was used to numerically track student behaviors and included the variable problem-solving skills which was characterized by behaviors of actively looking for and suggesting solutions to the problem and being willing to compromise. Findings of the study indicated that student participation in ER team challenges resulted in enhanced problem-solving skills and improved attitudes toward collaboration compared to when math tasks were completed in teams. Ref. [33] explored the actual problem-solving processes that age 11–12 elementary school students used during ER activities. The authors compared two groups as they problem-solved and found that both teams used a trial-and-error strategy, however the group that drew on classroom experiences and skills taught in previous classes was found to be more effective at problem-solving. The team that did not draw on prior classroom knowledge eventually resorted to "an unsolved trial-error-trial loop" (p. 2856). In the study by [35], the author investigated how elementary and secondary school students (n = 445) used EV3 Mindstorms robotics kits to solve two challenges. Data were analyzed through machine learning techniques and three problem-solving approaches emerged. The mathematical/planning style was where students used a well-defined mathematical strategy such as formulars to create a program, so fewer changes were made to the program sequence; testing was done for verification and fewer trials were observed overall. The tinkering style began with the use of practical experiences to propose a solution and two types of tinkering approaches were exhibited by students. "Tinkering with prevalent refining behaviour" was characterized by students' testing the program, analyzing the robots feedback, and then refining the block values by making small changes to get incrementally closer to the desired result. The "Tinkering with significantly high changes" approach was characterized by students analyzing the robot feedback and making major changes to the program sequence resulting in the need for multiple tests to be performed and these groups exhibited a higher number of total trials. The qualitative study [34] with 23 grade 6 students also indicated that participation in ER activities promoted student reflection on problem-solving decisions. These prior studies, however, investigating problem-solving processes during ER activities, were conducted with k-12 school students.

The few studies that have investigated PTs in ER contexts (e.g., [25, 36, 37]) examined the effect of the ER intervention on other factors or learning outcomes. Ref. [36] used pre-post test instruments to investigate the effect of the ER intervention on PTs computational thinking. Ref. [37] investigated the effect of the ER intervention to enhance PTs STEM engagement, learning, and lesson design through interviews and surveys. Ref. [25] did use a self-report questionnaire to examine how designing ER learning activities to teach programming content impacted multiple variables such as PTs interest, self-confidence, ER knowledge, and problem-solving skills. The latter three studies did not provide specific insights about the problem-solving processes PTs engaged in during the collaborative ER tasks. The current study provides in-depth analyzes of the problem-solving processes that elementary PTs engaged in as they used ER to solve a STEM task.

2.3 STEM problem-solving frameworks

Various problem-solving models have been proposed in the different STEM disciplines such as [38] model in mathematics which consists of the following stages: understand the problem, devise a plan, carry out the plan, and look back; [39] model for inquiry in science encompassing the stages: setting general parameters, organizing what we know and want to know, generating a testable hypothesis, seeking evidence, and constructing a scientific argument; and the engineering and technology model by [40] consisting of the phases—describe the current situation, identify needs, develop criteria, generate alternatives, choose an alternative, create prototype/test, and reflect and evaluate. Ref. [41] describe problem solving in computer science as involving the formulation of problems to use a computer and other tools to help solve them by logically analyzing the situation or problem; decomposing the problem into steps, using algorithmic thinking to create a series of ordered steps, using abstraction (hiding attributes) to simplify data and identify patterns, testing and debugging, and implementing and evaluating possible solutions based on goals and constraints. Ref. [42] has also proposed a general problem-solving model that includes the following stages: recognizing that a problem situation exists, establishing an understanding of the nature of the situation, identifying the specific problem(s) to be solved, planning a solution, carrying out a solution, and monitoring and evaluating progress throughout the activity. With recent curricular changes to integrate the learning of STEM skills into Ontario school curricula [3], the expectation is that students are to be exposed to problems and issues that are interdisciplinary and include scientific, mathematical, engineering, technological skills and computational ways of thinking. Since problem-solving is an intrinsic activity in the STEM disciplines and computer science, [43] argue that the problem-solving approach can serve as a common approach in teaching in all these disciplines. As such, a problem-solving framework that is applicable to all STEM domains would be relevant to apply in interdisciplinary contexts such as ER.

Ref. [43] proposed a general problem-solving framework that describes the methods and practices applicable to interdisciplinary problems. Their model is based on a conceptual analysis of the different problem-solving models described in the literature. They combined the formal, structured, scientific and engineering design processes from all the STEM disciplines into a list as shown in **Table 1**.

Another model [12] has also been proposed as a general problem-solving framework across the science and engineering disciplines. This model is derived from an empirical study involving 52 scientists and engineer experts in STEM fields such as biology,

Steps of the STEM and computer science framework of problem-solving
1. Noticing/generating a problem, phenomenon, observation, example, exception, irregularity, or situation
2. Exploring, examining, trial-and-error, tinkering, optimizing, guessing, or discovering
3. Specifying a problem, identifying needs, asking a question, stating a hypothesis
4. or conjecture
5. Making predictions, developing criteria, assuming relations, or checking existing theories
6. Developing explanations and solutions, generating and choosing alternatives, planning a proof, design, test or experiment, building models, collecting tools
7. Deducting, proofing, or finding counter-examples
8. Conducting a test or experiment, creating a prototype, using models, testing solutions, or computing
9. Generating data or observing
10. Manipulating, organizing, and representing data, categorizing observations, or choosing an alternative
11. Evaluating data and observations or making validations
12. Rejecting or supporting and refuting or accepting a hypothesis/solution
13. Making inferences, interpreting, reflecting on results and methods, embedding in contexts, or making conclusions
14. Communicating results and methods

Table 1.
STEM and computer science framework for problem-solving ([43], p. 118).

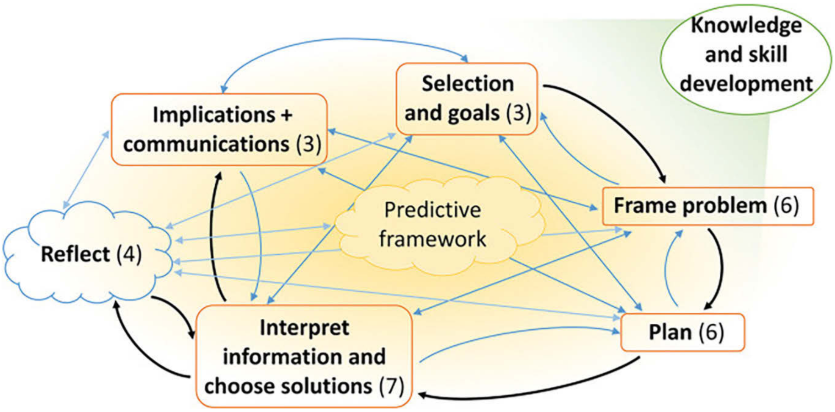


Figure 1.
Problem-solving processes of science and engineering experts as characterized by [12]. Note: The black lines represent the hypothetical order of the process and the blue lines represent the more realistic interactions among the categories. Each number represents the number of decisions in each category.

medicine, physics, chemistry, engineering and computer science. The authors identified the common decisions made by STEM experts during problem solving and grouped these into categories as illustrated in **Figure 1**. Permission to reproduce **Figure 1** is obtained through the "Attribution–Non-commercial–Share Alike 3.0 Unported Creative Commons License (http://creativecommons.org/licenses/by-nc-sa/3.0)."

The decisions made at each category of the problem-solving process, as found by [12], are listed in **Table 2**. Some of the decisions are similar to the specific processes highlighted in the [43] model such as asking questions, choosing solutions, and testing.

Problem-solving category	Decisions made
Frame problem	1. What are important features, concepts, information, representations of problem? 2. What predictive framework to use? 3. How to narrow down the problem through questions and hypotheses. 4. What are related problems or work seen before (review literature or reflecting on prior experience) 5. What are potential solutions (identifying key features and fitting some criteria for solution) 6. Is problem solvable in view of constraints and risks
Plan the process for solving	1. How to simplify the problem and test the approximations against established criteria 2. How to decompose the problem into sub-problems or smaller steps 3. Identify areas of uncertainty and difficulty 4. What information is needed to solve the problem to test and distinguish potential solutions 5. What to prioritize? Constraints, cost, resources, etc. 6. How to obtain information including specific plan of getting information and how to carry out problem solving plan such as designing, conducting experiments, etc. What are other possible alternative outcomes?

Problem-solving category	Decisions made
Interpret information and choose solution(s)	1. What calculations and data analysis are needed? 2. How to represent and organize information? 3. How believable is information (validity, reliability, and biases)? 4. How does new information from experiments or calculations compare to expected results? 5. How to follow up on anomalies? 6. What are appropriate conclusions based on data? 7. What is the best solution?
Reflect	1. Are assumptions and simplifications still appropriate? 2. Is more information needed and if so, what? 3. How well the approach is working and are modifications needed? 4. How good are the potential solutions? Can test failing options or see if it meets goals/criteria?
Implications and communication of results	1. What are broader implications of results? 2. Who is the audience to communicate the work? 3. What is the best way to present the work?

Table 2.
Decisions made by STEM experts at each problem-solving category.

Since the nature of the problem-solving activity occurring in this study is unstructured and the initial problem is given to students – to figure out how to park a robot (car) autonomously—the more general decisions for problem-solving in terms of the kinds of questions asked at each stage, as illustrated in **Table 2**, offer a flexible framework to analyze the study data.

3. Methodology and procedures

3.1 Study design

A qualitative, comparative case study [44] was conducted to understand how groups of PTs engaged in problem-solving during an ER activity. The study was guided by the broad research question:

How did PTs problem-solve in groups using ER?

The specific research focus was:

What decisions did PTs make as they engaged in STEM problem-solving using ER?

Since the goal of the study was to gain rich insights into the problem-solving process as experienced by preservice teachers during the robotics activity, five PT groups were selected through purposeful sampling for cross-case analysis. The selection criteria were based on having an audio-recording of high quality, a recording of the entire problem-solving task, and the presence of multiple sources of data for triangulation purposes. While the findings of case studies do not seek to be generalizable nor are they generalizable to the larger population, the rich details in a case study make the findings transferable—findings can be applied by the reader to another situation or context by making connections which can inform decision-making in these other contexts [45].

3.2 Participants

Study participants were preservice teachers in the first year of a Bachelor of Education program at a university in Ontario, Canada, being certified to teach grades 4–10 science. The PT participants for this analysis were from two class sections of a science and technology methods course taught by another instructor and the robotics activities were incorporated as part of the course curriculum. Since preservice teachers were in pre-assigned sections of courses, the study sample was a convenience sample and was representative of the unique population of JI preservice teachers at this university in Ontario. A total of 42 preservice teachers across the two classes provided their consent— 32 females and 10 males. From a total of 13 groups, six groups met all selection criteria. There were 12 females and four male participants in total in the cross-case analysis.

3.3 Setting and robotics activity

The study occurred in April 2022 when COVID restrictions were in place. As such university ethics approval protocols included addressing how to conduct activities to minimize COVID transmission. Preservice teachers had to wear masks and work in small groups that were spaced out in the laboratory. Hand sanitizers were provided at each workstation. Ethics protocols also included having a research assistant invite PTs to participate in the study and inform them that the activities were part of the course curriculum and were not being graded. While participation in the activities were required, participation in the research components were voluntary and PTs could refuse to be audio-recorded and could choose to have their data removed at any time. Prior to doing the robotics activity, PTs participated in course activities related to science and technology unit planning, assessments in science, environmental education, cross-curricular literacy connections, and science micro-teaching. PTs therefore did not experience any type of problem-solving activities involving robotics and coding.

The robotics activity was facilitated by the author during a 3-hour class session in the two class sections, respectively. During the ER session, PTs worked in dyads or groups of 3 to build and code a driving base robot using the *LEGO*® Mindstorms® EV3 kits. The instructor first introduced students to robots, basic programming concepts, and the robotics kits using a PowerPoint. Thereafter, PTs were provided with an overview of the robotics activity and a brief demonstration of how to use the programming software. PTs then followed instructions on a worksheet independently, to construct the driving base robot, complete a sequence of simple to more complex programming tasks, and then they solved an authentic, real-world problem—to park the driving base autonomously using parallel or perpendicular parking.

3.4 Data collection methods and analysis

Multiple data sources included:

- A worksheet where PTs recorded the problem-solving steps and programs used to solve the task

- Audio recordings of the discourse of participating PT groups using an iPad
- Photographs of robotics programs on the computer screen
- Video recordings of PTs demonstrating the parking of the autonomous driving base robot.

Data analysis began by reviewing the data of all groups in the two class sections to see which groups met the selection criteria. After the six groups were identified, the audiotapes were played to check the accuracy of transcripts. The six transcripts of group interactions were then read multiple times to identify emergent codes and patterns, as well as a priori codes and phrases indicative of the problem-solving decisions and categories described in **Table 2**. Themes and categories were then compared across the six cases to identify common (or different) problem-solving decisions and categories.

4. Results: preservice teachers' STEM problem-solving decisions during ER activities

The cross-case analysis of 6 groups of PTs about how they problem-solved during a robotics activity to park a car autonomously revealed similar categories of problem-solving as described by [12]. The analysis also revealed that the decisions made during the problem-solving scenario were, not unexpectedly, limited in scope and depth when compared to experts in STEM fields. Referring to the categories in the framework for STEM problem-solving [12], the first category, selection and goals of the problem, was not observed as PTs were provided with the problem and the goals of the problem as part of a structured learning class activity. Hence, the first problem-solving category identified among PT groups was *framing the problem*. This category was characterized by PTs making decisions to address the question: what are related problems or work seen before? The second problem-solving category identified was *planning the process for solving*. PT participants, in groups, planned the process by considering questions of how to decompose the problem into smaller steps and/or how to simplify the problem and test the approximations against established criteria. The third problem-solving category observed was *interpreting information and choosing solutions* and the main question considered by PTs in this category was: how does new information from experiments (in this activity, tinkering), compare to expected results? The fourth category observed was *reflecting* and some questions considered during this stage were: How well is the approach working and are modifications needed? and, How good is the potential solution and does it meet goals/criteria? The final category identified was *communication of results*. PTs presented their solutions on the computer, wrote them on the worksheets, and demonstrated the parking of the driving base. The aforementioned problem-solving categories/themes are interpreted below, supported with evidence from transcripts of audio-recordings of group interactions, and photo and video artifacts. The cases analyzed involved PTs programming a driving base robot to execute parallel or perpendicular parking autonomously.

The composition of groups and the type of parking were as follows:

Group 1 – one male and one female; parallel parking.

Group 2 – three females; parallel parking.

Group 3 – three males; parallel parking.

Group 4 – three females; parallel parking.
Group 5 – two females; perpendicular parking.
Group 6 – three females; perpendicular parking.

4.1 Framing the problem: drawing on prior, practical experiences of parking in real situations and creating a physical, small scale parking simulation

All PT groups began the problem-solving process by drawing on memories of prior experiences of parking to visualize how to frame the problem. Groups visualized aloud the process of how they would park in relation to a real parking scenario as illustrated in excerpts from transcripts of group discourse in groups 2, 3, 4 and 5 respectively.

> *Speaker 3: Okay. So, you know what you taught us in July. Start right here and then you go...*
>
> *Speaker 2: Line your mirror up with the mirror of the other car.*
>
> *Speaker 3: Yeah.*
>
> *Speaker 1: Okay So we're going to start off here. Okay.*
>
> *Speaker 2: This is the front.*
>
> [Transcript, Group 2, three females]
>
> *Speaker 2: So are we going to pretend that this is like a road. Do you guys want to put like fake pylons or something.*
>
> *Speaker 1: Just so we have a barrier for reference. When I think about parallel parking, you come up.*
>
> *Speaker 2: Yeah.*
>
> *Speaker 1: Maybe we'll start back here. We'll pull up past the spot and then we'll back into it, okay?*
>
> [Transcript, Group 3, three males]
>
> *Speaker 3: Well, parallel parking, let's just do parallel—because you have to move forwards, backwards, turn, back, turn again. It depends on how you actually drive, but I can [inaudible 00:00:54] parallel park. The first step is you pull up forward, it's like...Let's use...[puts two barriers to create parking space]*
>
> *Speaker 1: Yeah, so you drive forward.*
>
> *Speaker 3: You want to go past this one [cell phone], and then there's that one [pencil case], and you want to go there, right? So, you would drive up, or at least that's how I do it. I drive up parallel to the car to be in line, and then I turn, move backward, so like halfway, until, then I need to turn my wheel the other way, and then go backward and smooth it out.*
>
> [Transcript, Group 4, three females]

Five PT groups, groups 1, 2, 3, 4, and 6 used physical objects to set up barriers to create a small-scale simulation of a real parking situation (see **Figures 2**–**4** respectively). PTs in group 4 also drew a detailed diagram as part of their visualization of how to frame the parking solution (**Figure 5**).

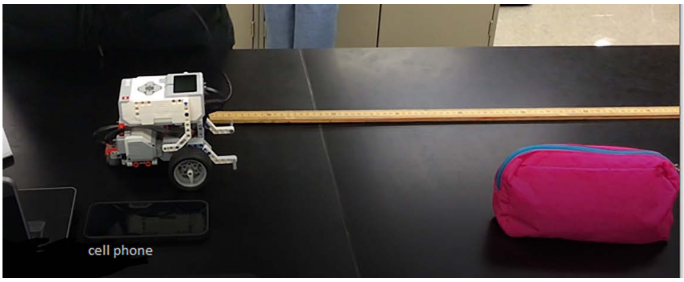


Figure 2.
Group 4: Simulating a parallel parking space with a cell phone and pencil case.

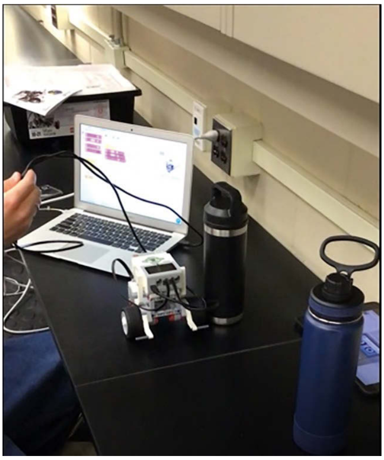


Figure 3.
Group 1: Simulating a parallel parking space with two water bottles.

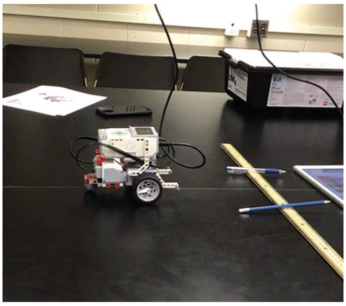


Figure 4.
Group 6: Simulating a perpendicular parking space with two pencils.

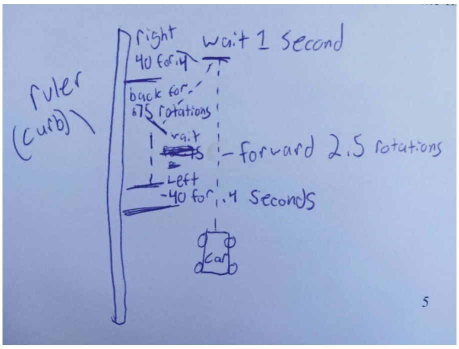


Figure 5.
Group 3: Diagram to visualize parallel parking.

PTs in group 5 did not use any physical objects to create a simulated parking space; they decided to pull into an imaginary parking spot and visualized aloud the steps for the perpendicular parking as illustrated in the excerpt below.

> *Speaker 3: I think perpendicular parking is pulling into a spot.*
>
> *Speaker 2: Okay. Well, this is the spot we are pulling into.*
>
> [Transcript, Group 6, three females]

4.2 Planning to solve the problem: decomposing the problem and drawing on basic STEM criteria

Five of the six PT groups decomposed the parking process into smaller steps and identified basic parameters such as the mathematics criteria they needed to figure out distance. In groups 2, 3, 4, 5 and 6, PTs calculated how far to move the car by using the distance the car traveled in one rotation of the driving base wheel. Since the math concepts were not reviewed in prior classes, hints were provided on the worksheet on how to calculate the distance traveled by one rotation of the wheel. The following sample excerpts illustrate how PTs drew on the provided STEM knowledge (i.e., math concepts) to figure out how to solve the problem of autonomously parking a LEGO driving base. The problem was decomposed into a series of smaller steps and mathematics concepts were used to figure where to position the driving base to begin the motion and how far to travel.

> *Speaker 3: This is the back, right? You need to back up, like maybe one or two wheels. We need to figure out how far we need to back up because we know one car is 17.5 centimeters, so how far do you need to move it backwards? Do that before your tire rotation.*
>
> *Speaker 1: Yeah.*
>
> *Speaker 3: Okay, so if we started right here, basically, we can start it [driving base] at 17, back one car. So, then it [driving base] would be here. So that's where it would go to.*
>
> [Transcript, Group 2, three females]

> *Speaker 1: Maybe we'll start back here. We'll pull up past the spot and then we'll back into it, okay? So first let's find out how far forward we have to go. So, we know that if we move forward for one rotation it goes forward for 17.5 centimeters roughly.*
>
> [Transcript, Group 3, three males]
>
> *Speaker 3: If you start from here, you'd need to move forward on the first step.*
>
> *Speaker 2: Yeah, I would say one rotation, like this.*
>
> *Speaker 3: Well, now would you go up 16?*
>
> *Speaker 2: Well, even if we do it right here, can we start it in line with these other cars*
>
> *Speaker 3: And we need to pull... the front of it would need to be here, so like 15, 16.*
>
> *Speaker 2: I would say you need to move three rotations, that's roughly 17 then 51, so you come up here.*
>
> *Speaker 1: Okay.*
>
> [Transcript, Group 4, three females]
>
> *Speaker 1: How do we do this [perpendicular parking]?*
>
> *Speaker 3. Yeah, let's start on this side here.*
>
> *Speaker 2: Move forward. Like you want to go forward, turn, forward.*
>
> *Speaker 1. Yeah.*
>
> *Speaker 2: So, can I try moving forward one rotation or do I use half a rotation?*
>
> *Speaker 3: Well, we know one rotation is 17 centimeters. I think that's too much.*
>
> *Speaker 1: That's true*
>
> [Transcript, group 6, three females]

PTs in group 1, however, did not spend time decomposing the parallel parking problem into a series of steps initially and did not draw explicitly on the mathematics hints to figure out distance. They drew on prior experiences of parallel parking and tried to use commonsense reasoning to deduce they would start with a 45 degree turn into the parking spot. They then tested this step and when it did not work, they tried to figure out the next steps of the parking sequence through guesses as illustrated in the excerpt from the transcript below.

> *Speaker 2: Yes. Okay. So realistically, when you reverse park in real life, it's like a 45-degree kind of...*

> *Speaker 1: Yeah, I always go like...yeah.*
>
> *Speaker 2: So, I feel like if we maybe start, try with 45 degrees. So, we can do, move right, 45 degrees. Does that make sense?*
>
> *Speaker 1: I feel that's going to turn it.*
>
> *Speaker 2: I know. I don't know, I have no idea.*
>
> *Speaker 1: Oh, but we want it to, I guess.*
>
> *Speaker 2: Okay. We've got to figure out which way it's going to move. Let's just make it move. [testing] That was close. So, we need to go longer and maybe less degrees.*
>
> *Speaker 1: I think the degree is fine. Wait, I guess something went wrong, the degree has to...*
>
> *Speaker 2: But what if we did that and then we made it go straight back?*
>
> *Speaker 1: Okay.*
>
> *Speaker 2: Shall we try that?*
>
> *Speaker 1: Yeah.*
>
> [Transcript, Group 1, male and female]

4.3 Interpreting information and choosing solutions: testing by trial and error to assess information and choose a solution

All groups tested their programs by testing each step, and as errors were identified in each step of the program, mostly incremental changes were made to values in each step, and then retested. This process of trial and error was repeated multiple times until PT groups felt that their solutions were successful at parking the driving base autonomously. A successful parking solution was, for example, when the driving base did not knock into any barriers or was finally parked in a straight line. Three sample excerpts are presented to illustrate the iterative process of trial and error with incremental changes made during problem-solving by these groups.

PTs in group 3, followed their parking plan on a diagram (**Figure 5**) and tested each step to figure out how effective it was. The excerpt below shows how they tested the first step of their parallel parking solution, changed the distance in rotations from 2 rotations to 2.5 rotations to achieve the desired movement that was closest to what they desired as the outcome. They then proceeded to test the next step.

> *Speaker 1: Let's see what happens if we do move forward for 2 rotations. Let's see how far we have gone. [testing] Good, maybe a little bit further. Let's say 2.5*
>
> *Speaker 2: Yeah, because when you do parallel park, your back wheel goes up to the front of your back door.*

> *Speaker 1: Yeah, so you are moving another half rotation forward. [adjusting to 2.5]. Back to our starting point. Try again. Okay, so now I think we've moved forward enough. So, now we need to come backwards and in.*
>
> [Transcript, Group 3, 3 males]

PTs in group 5, in the excerpt below, made incremental changes to step 2 of their program by adjusting the rotation value from 0.5 to 1.0 and then to 1.5 during the trial and error testing.

> *Speaker 2: I'm going to try. I just want to see where it gets to. [testing]*
>
> *Speaker 1: Okay.*
>
> *Speaker 2: We need 1. That was half [0.5] rotation.*
>
> *Speaker 1: We definitely need 1 and they need to turn 90 degrees.*
>
> *Speaker 2: Okay, bring them back.*
>
> *Speaker 1: Yep. [testing] Yes, we should probably be starting at the exact same spot again.*
>
> *Speaker 2: We should probably move it out so we can pull into it [parking spot].*
>
> *Okay, ready. [test]*
>
> *Speaker 1: Try 1.5.*
>
> *Speaker 2: I would say that's going to work.*
>
> [Transcript, Group 5, 2 females]

The next excerpt below shows how PTs in group 2 changed angles and distances in their 6-step program (which included wait times) through a series of iterative testing with incremental changes made to some values.

> *Speaker 1: Okay, we're trying to parallel park.*
>
> *Speaker 2: Do I just press it on here?*
>
> *Speaker 1: Yeah.*
>
> *Speaker 2: [testing]*
>
> *Speaker 1: Oh. It would work. Okay, so we just have gone too far then.*
>
> *Speaker 2: That [angle] needs to be wider. [changes angle and tests]*
>
> *Speaker 1: That's good.*

> *Speaker 2: It's supposed to go back more. I think we're robotic engineers. So, which one needs ....*
>
> *Speaker 3: Backwards for more than a second, right?*
>
> *Speaker 2: Yeah. 1.5 maybe?*
>
> *Speaker 1: Like triple the distance.*
>
> *Speaker 3: And then would it have to be, right.*
>
> *Speaker 2: I think so because it was still straight. Let's try it. [testing]*
>
> [Transcript, Group 2, 3 females]

4.4 Reflecting on proposed solutions: using instant feedback from driving base robot and gaining pedagogical insights

All groups reflected on how well their proposed solutions worked by observing how effective the program was at executing the steps of the parking during the testing process. They responded to the instant feedback from the driving base robot and gained insights into how to improve the parking program solution. For example, PTs in group 4 reflected on step 5 of their program by considering the need to add a wait time after moving backwards based on what they would do when parking a real car.

> *Speaker 3: Yeah, so it does need to... It actually needs to move backwards for one second, then turn.*
>
> *Speaker 1: Yeah.*
>
> *Speaker 2: So, move back one second, and then turn [adjusting the program].*
>
> *Speaker 3: Let's just test it. If we move backward...*
>
> *Speaker 2: Well, should we do for 1.25 rotations and wait one second?*
>
> *Speaker 3: Yes. Because when I would—when you drive, you don't just instantly go back.*
>
> [Transcript, Group 4, 3 females]

PTs in group 6, doing perpendicular parking, reflected on the instant feedback from the driving base robot and added a wait time after step 2 of their program. They also realized the importance of marking the starting spot to figure out how far to move.

> *Speaker 2: 90 degrees. How many rotations?*
>
> *Speaker 1: Turn left. Start with one. Depends on how far we are from the spot.*
>
> *And we honestly need a marker from where we're starting here.*

> *Speaker 3: [testing]. Oh, its 45, 45.*
>
> *Speaker 2: Okay, you can bring it back.*
>
> *Speaker 1: That was not smooth at all. Wait one second.*
>
> *Speaker 2: I'm just going to add it right now. Wait one second, and then, forward.*
>
> [Transcript, Group 6, 3 females]

Groups also reflected on the final solution at the end of the testing process, making final modifications to values before settling on the solution as illustrated by groups 1, 4 and 6.

> *Speaker 3: There you go.*
>
> *Speaker 1: That's pretty good.*
>
> *Speaker 2: Yeah.*
>
> *Speaker 1: I don't know if we're going to get any*
>
> *Speaker 2 more perfect.*
>
> *Speaker 1: more perfect than that. Maybe let's try back just a little bit further, 1.5. We'll see if that makes any difference. [adjusting value and testing]*
>
> *Speaker 2: That's perfect.*
>
> [Transcript, Group 1, male and female]
>
> *Speaker 2: We're close, though.*
>
> *Speaker 3: We're close, but it went like...I mean, it needs to go just a little bit more backwards. [adjusts value] Okay, now it's [inaudible 00:15:34].*
>
> *Speaker 2: It's fine.*
>
> [Transcript, Group 4, 3 females]
>
> *Speaker 2: Is it negative 55?*
>
> *Speaker 1: Yeah.*
>
> *Speaker 3: Let's line it up again. I want to videotape it.*
>
> *Speaker 2: [testing] It was about there. [testing]*
>
> *Speaker 3: That was perfect.*
>
> [Transcript, Group 6, 3 females]

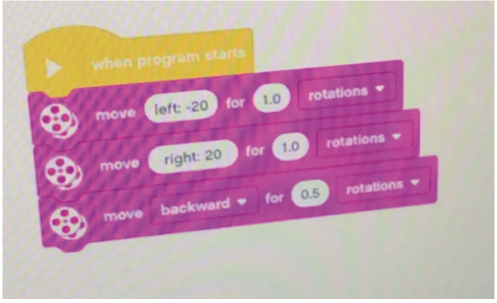
Reflecting on the instant driving base feedback during trial and error testing also enabled PTs in group 3, 5 and 6 to realize that they needed to mark the spot where the driving base began its motion to ensure that when the program was repeated, the driving base executed the same sequence of motion to fit in the parking spot created. When the driving base was placed at a different start position, it executed the same movements, but on a different path, causing the driving base to knock against the barriers. Two PTs in group 3 reflected on how they would use this insight when they taught the ER activity with students in schools.

> *Speaker 1: I think I started a little more in than the last time. We should have really marked this, somehow where we started.*
>
> *Speaker 2: Yes. Lesson learned. We'll make sure to tell students that mark where you are starting there.*
>
> [Transcript, Group 3, 3 males]

4.5 Communicating results: creating effective visual block program solutions on a computer and demonstrating parking

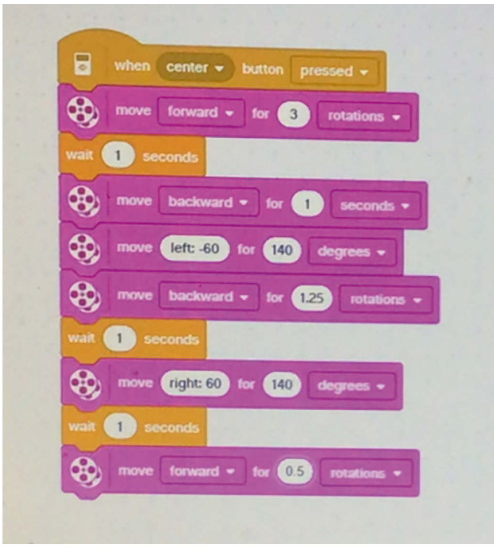
All groups created visual block programs for their parking problem using the Mindstorms computer application, recorded this on the worksheet provided, and demonstrated their solutions. However, there were differences in the complexity and effectiveness of the final program solutions created.

For example, in group 1, the two PTs created a three-line program based on a brief reflection of prior experience as shown in the transcript in 4.2. They did not use the mathematics hints and began to code by guessing what the angle values could be. They then used the trial and error process to change angle values randomly as indicated in the full transcript (90 to 45 to 33 to 57 to 40 to 25 and finally settled on 20). This PT group did not use wait times or start each trial at the same spot and had to make the parking space bigger to execute the parking. Group 1's final program solution for parallel parking is illustrated in **Figures 6** and 7 and demonstrated in Video 1 (https://www.youtube.com/shorts/CXkRD7c5NTY). On the other hand, PTs in group 4 decomposed the problem during the planning phase and used the math criteria on the worksheet to figure out angles for distances before testing as described in transcripts in 4.1 and 4.2. They then conducted multiple tests, also through trial and error, but reflection on instant feedback from the driving base enabled them to



```
when program starts
move left: -20 for 1.0 rotations
move right: 20 for 1.0 rotations
move backward for 0.5 rotations
```

Figure 6.
Group 1's computer program for parallel parking.



```
when center button pressed
move forward for 3 rotations
wait 1 seconds
move backward for 1 seconds
move left: -60 for 140 degrees
move backward for 1.25 rotations
wait 1 seconds
move right: 60 for 140 degrees
wait 1 seconds
move forward for 0.5 rotations
```

Figure 7.
Group 4's computer program for parallel parking.

realize the need to include wait times in their parallel parking solution. They did not, however, start parking at the same spot each time, so their parking demonstration, though correctly executed for parallel parking hit one of the barriers as shown in Video 2 (https://youtu.be/fQZhtuB4Gc4).

5. Discussion

The results of a cross-case analysis of how six groups of elementary, JI PTs solved the problem of parking a driving base robot autonomously, revealed insights into the nature of the problem-solving processes that PTs engaged in. The findings show that this sample of PTs exhibited a similar set of STEM problem-solving processes as proposed by [12]. However, the decisions PTs considered during the different stages or categories of STEM problem-solving when using ER were limited in scope compared to experts in the STEM fields. STEM experts' problem-solving processes include decomposing the problem into smaller steps, drawing on prior academic knowledge such as mathematics and physics to make precise calculations related to all parameters of the problem, doing error calculations, and creating codes and models so they can test a few programs and choose the best solution as efficiently as possible [12].

In the current study, the main resource all PT groups drew on during the process of framing the problem was prior knowledge related to practical, everyday experiences of the phenomenon—specifically practical experiences with parallel or perpendicular parking. PTs drawing on practical knowledge as a resource is not an unexpected result as most elementary PTs are novices in the STEM fields. Only 1% of PTs [3] from 32 PTs in the combined two sections, who responded to a pre-questionnaire in the current study, felt they had sufficient knowledge of robotics to use in teaching. Five of the six PT groups in the current study also used STEM knowledge such as the math calculation hints on the worksheet to plan their solutions and these solutions simulated closely the parking as done in a real parking scenario. The one group that used only practical knowledge as the basis for planning the solution for parallel parking, created a solution that worked to park the driving base robot as shown in the video 2 which may not have worked effectively in a real parking scenario due to the lack of wait-times. This finding about how STEM resources affected the solutions during the ER activity is similar to results observed in a study of middle school students—it was observed that the student group that relied on mainly practical knowledge and experiences for problem-solving was less successful at solving the problem than the group that also used prior STEM knowledge taught in previous classes to work out the solution to the ER problem [33].

PTs in the current study also considered fewer decisions than STEM experts when planning the process and interpreting information and choosing solutions. All six PT groups planned the parking solution based on their visualization of what they observed or experienced in a real parking situation. Five PT groups decomposed the practical parking experience into a set of smaller steps and conducted multiple trial and error testing and obtained instant feedback from the driving base robot. They used this feedback to systematically change the values in their programs, mainly in small increments, thereby refining their solutions to achieve the desired parking they had visualized. This tinkering approach to problem-solving was also identified in a study of 445 elementary and secondary school students and was referred to as "Tinkering with prevalent refining behaviour" [35]. The current study findings add to the findings of these other studies [33, 35] by showing that elementary PTs used a similar approach as that used by k-12 school students when problem-solving with ER. Both participant groups were STEM novices and used tinkering, characterized by trial and error feedback loops, to make small, incremental or random changes to obtain the desired problem outcome.

With respect to how PTs reflected during problem-solving, iterative testing enabled some PT groups in this study to reflect on the instant feedback and gain realizations that enhanced their initial solutions—4 groups added wait-times in their programs and 3 groups realized the importance of marking the spot where the parking began with one group articulating the pedagogical connection—the importance of alerting school students to mark the starting point when teaching the activity at schools. This PT group realized that marking the starting spot, to begin the parking, will help students at school minimize the number of trials and demonstrate parking solutions that work successfully. Higher number of trials during structured ER problems have been negatively correlated with elementary and secondary school students' ER solutions [35].

In the current study, PTs also participated hands-on, in an ER activity designed to meet the Ontario Science and Technology grade 8 curriculum expectations. The findings show (albeit with one PT group explicitly mentioning the importance of telling students to mark the starting spot for the parking and two other groups applying this insight in their own parking solutions) that providing opportunities for PTs to participate in ER activities designed for students in classrooms, can help PTs gain pedagogical insights to improve the ER activity design for implementation. Debriefing ER activities with PTs with a focus on its pedagogical applications in teaching, is another strategy to prompt all PTs to engage in reflection for teaching. Reflecting on technology-enhanced activities has been found to be effective at promoting PTs implementation of technology-enhanced activities [46]. Due to time limitations, the author did not conduct whole class debriefings with PTs in both class sections, but pedagogical implications were discussed with some groups when they demonstrated their final solutions. Furthermore, similar to findings of other studies of PTs and ER [25, 26], the findings of the current study show that PT participation in problem-solving activities with ER helped them learn how to problem-solve and create successful solutions. PTs success learning how to program a driving base robot to parallel or perpendicular park autonomously was demonstrated by the workable executions of the parking by all six groups.

Overall, the findings of the current study suggest that the quality of the parking solutions created by this sample of six PT groups and its effectiveness during the demonstration of the parking was related to the type of decisions that these PTs made during the STEM problem-solving. The PT group that used mainly prior practical knowledge to guide them through multiple trial and error testing based on guesses and did not add wait times, created a parking solution that would not be very effective in a real parking situation. The four groups that produced successful solutions used STEM knowledge to consider parameters that would affect the practical situation, decomposed the parking into smaller steps, and used trial and error iterations to make incremental changes, and added wait times.

What are some of the pedagogical implications of the findings for teacher educators? It is obvious that as teacher educators, we cannot expect middle school PTs, trained to be generalist teachers, to have the breadth and depth of academic knowledge related to the STEM subjects as STEM experts. It therefore becomes important for teacher educators to think of ways to support PTs engage in effective STEM problem-solving so that they gain knowledge and confidence to be able to teach with ER in schools. For example, teacher educators can provide salient STEM background knowledge to PTs to help minimize unsolved trial-error-trial feedback loops to enhance efficiency in problem-solving. Ideally, the STEM background knowledge would be taught as part of the methods course, but the latter is not always practical and doable. Traditionally, subject methods courses are taught as separate disciplines, with course content focused on that discipline. In this science and technology methods course, robotics is covered in one class of the 12-class course. Other classes in the course need to address science content and pedagogy topics such as environmental education, inquiry science, engineering design and learning to plan, teach, and assess science and technology across grades 4–10. Therefore, there is limited time to prepare PTs with the relevant background knowledge in other STEM subjects in the science methods course. It is recommended that teacher education programs sequence methods courses so that PTs are able to learn, for example, the math prior knowledge required for ER activities. Although PTs in this study had already completed a mathematics methods course prior to the study, the math methods course focuses on learning pedagogy and not specific math content knowledge so there is no certainty that PTs would have the pre-requite math knowledge. The strategy used in the current study was to provide PTs with relevant prior STEM knowledge as written hints on the worksheet—for example how car wheel rotation and distance were calculated. Of course, as educators know from experience, many students including PTs tend not to read worksheets. It is therefore important to also highlight the salient STEM information pertinent to the problem and/or provide PTs with some background STEM knowledge prior to the problem-solving activity.

Many PTs are also not familiar with coding and will need support in this area. The need for this support is reinforced by the findings that non-specialist teachers' lack of coding knowledge and skills affect the quality of student learning outcomes [23]. In the current study, the author adapted the strategy of scaffolded programming scripts (step-by-step coding from simple to complex) to help PTs learn to program [47]. Scaffolding for programming was provided through a set of simple coding exercises on the worksheet that began with how to program the driving base to turn and move. PTs then completed a simple challenge moving the driving base in a straight line which also enabled them to deduce the relationship between distance moved and number of rotations of the wheel before solving the parking problem. Learning to code through a series of coding exercises sequenced to scaffold learning from simple to complex has been shown to enhance programming skills among novice PTs [47, 48]. The current study therefore modeled for PTs how to use a scaffolding strategy to teach problem-solving with ER and contributes to developing PTs' confidence to teach science and technology concepts using ER. Activities that engage PTs in the learning of science and pedagogy have been shown to build PTs confidence to teach science [24]. The study in this chapter also provides a case exemplar of how elementary preservice teachers participated in a collaborative STEM problem-solving ER activity to learn STEM and learn how to teach STEM skills with ER and the findings can be used as a case study resource in teacher education STEM methods courses.

6. Limitations and future research

It is important to note that this study was a qualitative, comparative case study and the purpose of such designs are to understand and gain insights into the phenomenon—in this study to gain insights into how PTs problem-solved during an ER activity. Hence, sample sizes are small and insights from cases are meant to be applied by the reader to similar contexts and help them make decisions involving similar situations. Therefore, the findings of this study are not generalizable to the larger population. Additionally, the problem-solving categories and decisions evidenced in this sample of PTs may not be evidenced in another sample of PTs with a different set of undergraduate and teacher education program experiences. Future studies could investigate how elementary PTs in other teacher education program contexts make decisions using similar ER problem-solving scenarios. Future studies can also compare problem-solving with ER between PTs who are STEM specialists (e.g. secondary pre-service teachers) and elementary, generalist PTs. Findings from such studies can provide insights into strategies teacher educators can use to support elementary and secondary PTs problem-solve with ER while learning to teach with ER. Another limitation is that only one problem task was analyzed. Future studies can investigate how PTs problem-solve using different STEM tasks to determine if similar decisions are made in multiple problem contexts. A final limitation is that this study explored problem-solving with one type of ER kit. It may be that findings may be different when using a different ER kit with a different set of technical requirements. Future studies can therefore investigate how PTs problem-solve with different ER kits and if different technical knowledge requirements affect the problem-solving process and effectiveness of solutions.

7. Conclusion

This study explored elementary, middle school (JI) PTs' problem-solving decisions when they used LEGO Mindstorms EV3 kits in small groups, to solve how to parallel or perpendicular park the driving base robot. The group interactions of six PT groups were compared and analyzed to identify similarities and differences in the problem-solving process using a STEM problem-solving framework [12]. Interpretations from the transcripts were triangulated with written programs on a worksheet and the computer, and videos and photos of the execution of the final parking solution. The cross-case analysis revealed that elementary PTs, as novice STEM problem-solvers, not surprisingly, exhibited fewer decisions at the different stages of problem-solving as proposed in the framework [12]. The findings indicated that successful problem solutions were created by PT groups who framed the problem by (1) considering practical knowledge from experiences with the phenomena and drawing on STEM knowledge (i.e., math calculations), (2) planned the process to solve by decomposing the problem into smaller steps, (3) interpreted information from instant feedback, ascertained through iterative, trial and error testing, to make incremental changes to obtain solutions, and (4) reflected at all stages of the problem-solving process and modified solutions (e.g., adding wait time) when solutions did not work as well as expected. By having PTs experience problem-solving with ER through scaffolded activities designed for elementary school students, PTs not only learned STEM skills, but they also gain opportunities to reflect on pedagogy to inform design and implementation of the ER learning activities for elementary school students.

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Chapter 6

Perspective Chapter: Building a Multisector STEM Learning Ecosystem at the San Antonio Museum of Science and Technology

Cliff Zintgraff, Michael Thoennes, Joshua Martinez and Giselle De Leon

Abstract

SAMSAT, the San Antonio Museum of Science and Technology, has built a STEM learning ecosystem for its immediate community, and for the city working with partners. The work is centered at Port San Antonio, a former Air Force Base campus and SAMSAT's host and partner. This chapter qualitatively describes the effort, including how research and data informs our work. Building on our museum platform and Port redevelopment, SAMSAT engages K-12, industry, academia, government, and non-profits, channeling the campus's energy. The chapter includes brief history and context. It describes our education strategy of inspiration, engagement, and pathways. It highlights models, pedagogy, local and national partnerships, and measurement and evaluation. Four programs are described: a structural engineering course for middle schools, an eclipse celebration, our Mayor's smart city challenge, and our citywide esports league. We close describing connections to social-emotional learning, and practices that help transform lives in our community.

Keywords: STEM, informal learning, STEM ecosystems, education pathways, partnerships

1. Introduction

SAMSAT, the San Antonio Museum of Science and Technology, located in San Antonio, Texas, USA, is a young museum that has built a STEM learning ecosystem serving students and families, especially those from underserved populations. We operate a museum, deliver educational programming, and help students prepare for STEM careers. In the most recent calendar year, we served 24,000 students. The immediate community around SAMSAT, who we primarily serve, is among the most economically segregated in the U.S. [1]. We also help lead a larger city ecosystem, and we are part of a national ecosystem [2]. Our mission is to make a transformative impact on the students, families, and communities we serve [3].

Our story is centered at Port San Antonio [4]. The name refers to both the campus where we reside and the organization that oversees its development. The Port organization was formed to redevelop a closed Air Force base. The 10,000 jobs lost as the base closed between 1995 and 2000 led in large measure to the economic challenges of our immediate community. SAMSAT is located at the Port, collaborates with campus-based and other partners, and channels the Port's energy into STEM awareness, education and pathways. We are part of the Port's larger economic development ecosystem that hosts 18,000 jobs on the redeveloped campus. For the reader's context, we note that this port is air and rail, not sea, and that Port operations are just one of many economic activities.

SAMSAT's ecosystem builds on models for policy development, ecosystem development, and STEM pedagogical best practices. Among these are the STEM Technopolis Model [5], project-based learning [6], and underlying philosophies of constructivism [7] and constructionism [8]. These approaches underly our policy, partnership and teaching practices, and our education strategy: inspiration, engagement and pathways. Programs that feature partnerships, mentors and interns will be described. We close with a summary of connections to social and emotional factors, and best practice takeaways that we believe are helping us transform lives in our community.

2. Brief history and context

2.1 Port San Antonio

In response to the changing geopolitical landscape of the 1990s, the United States government closed numerous military bases. A commission in 1995 voted to close San Antonio's Kelly AFB, realigning its runway to the adjacent Lackland AFB, and transferring control of remaining space to the City of San Antonio. A redevelopment agency was formed that came to be known as Port San Antonio [9].

Like many bases, Kelly AFB was part of its host city's culture. San Antonio identifies as Military City USA® [10]. When first listed for possible closure, 35,000 workers and others turned out in a show of support. Mayor Nelson Wolff shared that "for generations of Hispanic families, [Kelly] pulled them out of poverty, it gave them hope...was the key factor in offering upward mobility for Hispanics" ([11], para. 3). San Antonio, the seventh largest city in the U.S. with a population approaching 1.5 million residents, is a majority-minority city, with a Hispanic population of 64% [12]. Kelly's closure created a strong negative economic impact on the surrounding community, with disproportionate effect on the Hispanic population.

Almost 30 years later, Port San Antonio is home to 18,000 jobs. The new Boeing Center at Tech Port, a 130,000 square foot (12,000 square meter) entertainment, community, technology transfer, and STEM outreach center is home to SAMSAT AREA 21®, SAMSAT's flagship museum space. Boeing San Antonio is Boeing's largest Maintenance and Repair Operation (MRO) facility in the U.S., and one of the largest military sites in the world [13]. Sixteenth Air Force, headquarters for U.S. Air Force cyber operations, is a hub for the local cyber community [14, 15]. San Antonio regularly cites itself as having the second highest number of certified information security professionals in the U.S. [16, 17]. **Figure 1** includes two of the neighborhoods that are immediately adjacent to the Port San Antonio campus, neighborhoods impacted by the closure of Kelly AFB.

Figure 1.
SAMSAT on the Port San Antonio campus, and nearby neighborhoods.

2.2 SAMSAT: The San Antonio Museum of Science and Technology

SAMSAT was founded in 2016 as a U.S. non-profit corporation. SAMSAT arrived in the Port's location and ecosystem in 2017. A second non-profit, SASTEMIC, co-located with SAMSAT at the Port and added its STEM education capacity to SAMSAT's museum platform through a merger in 2019. SAMSAT's core assets were a collection of museum quality artifacts assembled by founder David Monroe, with the collection including a World War II-era Enigma cipher machine; the Datapoint 2200, recognized by the Institute of Electrical and Electronics Engineers (IEEE) Region 5 as the first desktop computer [18]; and Edison Menlo Park experimental light bulbs. **Figure 2** shows examples of SAMSAT's exhibits and collection.

SAMSAT opened its flagship space in August of 2022. Named SAMSAT AREA 21®, the space has a limited number of the most significant historical artifacts while focusing on the present and future of technology. The 20,000 square foot (1850 square meter) space features factory floor robots, an autonomous driving Sport Utility Vehicle, a 385 square foot (36 square meter) Cyber/Critical Infrastructure City comprised of Lego bricks; a 12-large-screen Cyber Security Operations Center, a research prototype three-meter-tall Moon 3D printer from partner the WEX Foundation; Tesla coils; a robotic surgery system; and intern projects [19].

SAMSAT has a full offering of education programs that serve grades 3–12, including. 21DISCOVERY™ field trips, afterschool programs, school outreach, and summer

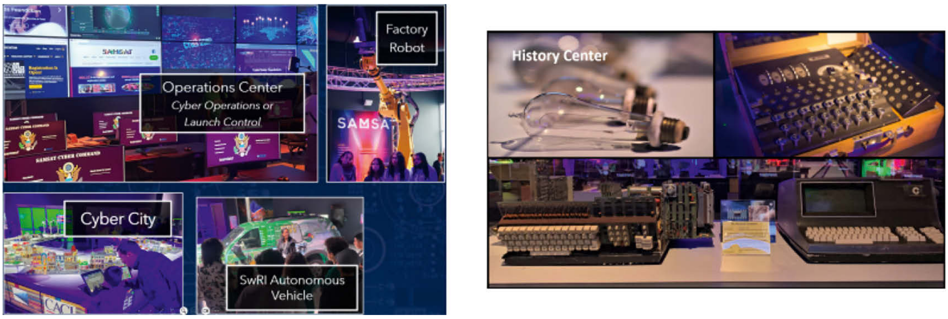

Figure 2.
SAMSAT AREA 21® and SAMSAT History Center.

camps. Sponsors enable multiple special programs, including Boeing STEM Academy, R20 Premiere Esports, the SA Smart Mayor's Smart City Challenge, Hurd Pathways, Boeing Pathways, Accenture Cyber, Joint Base San Antonio Cyber, and multiple programs that serve high school and college interns.

3. Policy, ecosystems, and pedagogy

SAMSAT's work is informed by models and philosophies of instruction that emphasize collaboration with partners, student voice and engagement, meaningful engagement with adult professionals and mentors, and connections to local priority education and career pathways. We believe these elements interact in mutually reinforcing ways that yield benefits for students, schools, industry partners, and the families and communities we serve.

3.1 The STEM Technopolis model

The original Technopolis Model [20] emerged from work in Austin, Texas, USA that led to the city's emergence as a global technology leader. The model treated different sectors in the community as spokes in a wheel whose collaborative efforts lead to forward motion. Building on that work, the STEM Technopolis Model illustrated in **Figure 3** [5] views the work through the lens of STEM education and development. It elevates the role of primary and secondary (in the U.S., "K-12") education as an equal player in the long-term economic development of regions.

A key concept in the STEM Technopolis Model is alignment with a city's or region's existing priority industry clusters. For example, San Antonio is home to a leading cybersecurity cluster, claiming the second highest number of certified information security professionals in the U.S. [16, 17]. Local education programs that focus on cyber find a relative wealth of volunteers, mentors, industry partners, and program funding.

3.2 STEM learning ecosystems

STEM learning ecosystems are "cross-sector collaborations [that] deliver rigorous, effective preK-16 instruction in STEM learning…they spark young people's engagement, develop their knowledge, strengthen their persistence and nurture their sense of identity and belonging in STEM…[connect] with real-world learning opportunities, leading to STEM-related careers and opportunities" ([21], para. 2).

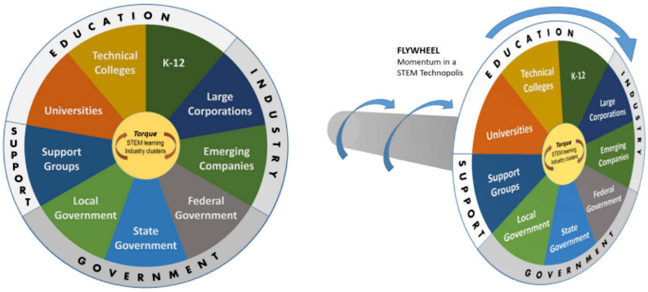

Figure 3.
The STEM Technopolis model [5].

SAMSAT is actively building and participating in STEM learning ecosystems. This work drives knowledge sharing and is a pipeline for funding, partner, and program opportunities. We view our work centered at Port San Antonio as the building of a local STEM learning ecosystem.

SAMSAT co-leads the Alamo STEM Ecosystem (ASE) alongside the Intercultural Development and Research Association (IDRA). ASE includes an estimated 30 San Antonio-area organizations including schools, colleges and universities, non-profits, government, and industry. In this work, we collaborate with partners across all technopolis sectors. In turn, ASE is a member of STEM Learning Ecosystems (SLE), a U.S. and global community of practice with 111 members [22]. ASE also hosts the Alamo (San Antonio) Hub of the Defense STEM Education Consortium (DSEC), a national program promoting civilian STEM careers. Through DSEC, we collaborate with additional local and national partners.

3.3 Pedagogy

SAMSAT embraces the learning philosophies of constructivism, constructionism, and connectivism. We use the PBLWORKS [6] models of project-based learning as guides for our work. These ideas inform how we think; how we select content; how we design curriculum and programs; how we deliver to students, teachers and schools; and how we integrate partners. Focus on these models represents an intentional move away from lecture, and a move toward project-based instruction.

Constructivism [7] reminds us that students construct their own knowledge, engaging with the objective world starting from their unique schema of prior knowledge. When a student learns something new, that student has a unique starting point. From the same content delivered by one teacher, each student’s ultimate learning is unique. As humans do, students add meaning to the objective world they encounter, meaning unique to each student.

Constructionism [8] reminds us of the power of creating new things, and of public presentation of those artifacts. We cannot know if a student understands new content until that student constructs a tangible object, a document, a presentation, or some other artifact. Awareness that the artifact will be seen publicly creates strong motivation for quality engagement and review.

Connectivism [23], while less acknowledged in the teaching and learning field, reminds us of core ideas relevant to SAMSAT’s daily work. Sometimes knowledge does not reside in one person, but only among a group or team. The capacity to learn new things, and to keep knowledge current, is sometimes more important than what a person or group already knows. There is great value in being able to make connections between seemingly unrelated ideas, and to view decision making as continued learning, not just a static outcome from applying static knowledge.

The methods of project-based learning are consistent with these philosophies. SAMSAT uses the PBLWORKS [6] models for project-based learning to inform program designs and curricula, and we use PBLWORKS directly in teacher professional development. We strive to incorporate inquiry, relevance, student voice, and public presentation of artifacts. We strive to integrate academic standards, and to let students learn from mistakes with support and scaffolding from instructors. We intentionally design, manage, and assess these efforts.

3.4 SAMSAT's education strategy: inspiration, engagement, and pathways

Our approach was summarized in an internal three-page document that is required reading for all education staff. From these sources and our lived experience, we arrived at the following strategy for SAMSAT's educational offering: inspiration, engagement, and pathways. We inspire students to consider STEM through appealing exhibits and programs. We engage students to help them feel what STEM is like on a day-to-day basis. For students who have shown interest in STEM as a career, we help them know, walk, and celebrate STEM education and career pathways.

Our education strategy completes a larger system that honors the lessons of the STEM Technopolis model. Through hands-on and relevant programs, the use of local priorities as topics, and the engagement of caring adults as volunteers, speakers and mentors, we leverage the energy and resources of our community to create great learning experiences for students.

4. Cross-sector partnerships

Partnerships are essential to SAMSAT's work. Our partnerships span all sectors: K-12, academia, industry, government, and non-profits. **Table 1** summarizes partnerships SAMSAT has held in the last 2 years. We define partnership as a close working relationship on a program that includes at least three instances of service delivery (most partnerships involve many more engagements). ISD refers to the Independent School Districts that govern K-12 schooling throughout the U.S. COSA refers to City of San Antonio departments. We share this level of detail to allow the reader to see the breadth and types of partners, the intended purposes, and to relate these details to each reader's local context.

Table 2 highlights attributes across these partnerships. The reader should note:

- Inspiration, engagement, and pathways are cumulative. Programs that engage also inspire. Pathway programs also engage and inspire.
- Rows indicate partners, not programs, and there are many cases where indicators reflect common underlying programs. For example, Boeing STEM Academy brings mentors to numerous ISDs.

Below, we briefly summarize some of the more robust partnerships and relevant programs. We refer the reader to the prior summary of our most important relationship with Port San Antonio, and to the prior description of the Alamo STEM Ecosystem. We call your attention to how these programs build on local San Antonio priorities and challenges.

4.1 Boeing STEM Academy

Boeing's largest facility for Maintenance and Repair Operations (MRO), and one of the largest throughout the military worldwide, is at Boeing San Antonio [13], located about one-half mile from SAMSAT AREA 21. Boeing has sponsored SAMSAT since 2019, with programs including summer camps, esports, SAMSAT AREA 21 tours, and pathway support. An estimated 5000 students have been served.

Partner	Program
K-12	
Edgewood ISD	Afterschool, Boeing STEM Academy
Harlandale ISD	Afterschool programs
San Antonio ISD	Cyber programs; formal MOU
South San ISD	Esports; afterschool
Northside ISD	Boeing STEM Academy
Northeast ISD	SA Smart Mayor's Challenge
Academia (Universities, Technical/Community Colleges)	
Texas A&M University-San Antonio	Esports; research proposals
University of Texas at San Antonio	Research proposals
Alamo (Community) Colleges	Internships; esports
Industry	
The Boeing Company	Boeing STEM Academy+
Firstmark Credit Union	Teacher professional development
Southwest Research Institute	Volunteers, intern support
CACI	Exhibit development
Intuitive Surgical	Exhibit development
IEEE	Exhibits, volunteers, mentors
Itron, Inc.	SA Smart; smart energy education
Government/Municipal	
Port San Antonio	Major sponsor
Office of Mayor Ron Nirenberg	SA Smart Mayor's Challenge
City Public Service (CPS) (Utility)	SA Smart; smart energy education
San Antonio Water System (SAWS)	SA Smart Mayor's Challenge
COSA Office of Innovation	SA Smart Mayor's Challenge
COSA Planning Department	SA Smart Mayor's Challenge
COSA Office of Sustainability	SA Smart Mayor's Challenge
COSA Parks and Recreation	SA Smart Mayor's Challenge
Joint Base San Antonio	Cyber programs
Non-Profits/Foundations	
WEX Foundation	Exhibits
NASEF	Esports
Salvation Army	Summer camps, afterschool
IDRA	ASE; DSEC
CyberTexas Foundation	Alamo STEM Ecosystem; DSEC
UP Partnership	Joint Leadership Table
Family Service Association	Interns
San Antonio Area Foundation	General support, and SA Smart

Partner	Program
Nancy Smith Hurd Foundation	Education pathways
Kronkosky Foundation	Character development
Alamo STEM Ecosystem	Ecosystem; DSEC

Table 1.
SAMSAT partnerships.

Partner	Inspire, engage, pathways	(V)olunteers, (M)entors	Special local focus	Donor (F)unding, (I)n-kind
K-12				
Edgewood ISD	Engage			
Harlandale ISD	Engage		water	
SAISD	Pathways	M	cyber	
South San ISD	Pathways	M	cyber	
Northside ISD	Pathways	M	multi	
Northeast ISD	Pathways	M	multi	
Academia (Universities, Technical/Community Colleges)				
TAMUSA	Pathways	M	esports	
UTSA	Pathways	M	cyber	
Alamo Coll.	Pathways	M	esports	
Industry				
Boeing	Pathways	VM	aviation	F
Firstmark	Engage	V		F
SwRI	Engage	M		I
CACI	Inspire	V	cyber	FI
Intuitive	Inspire			I
IEEE	Engage	VM		I
Northworks	Inspire			I
Itron, Inc.	Engage		multi	F
Government/Municipal				
Port SA	Pathways	VM	multi	FI
Mayor's Office	Engage	V	multi	
CPS	Engage	VM	multi	F
SAWS	Engage	VM	water	F
COSA Inno.	Engage	VM	multi	
COSA Planning	Engage	VM	multi	
COSA Sustain.	Engage	VM	multi	
COSA Parks	Engage	VM	multi	
Joint Base SA	Engage		cyber	F

Partner	Inspire, engage, pathways	(V)olunteers, (M)entors	Special local focus	Donor (F)unding, (I)n-kind
		Non-Profits/Foundations		
WEX	Engage	VM	aero	I
NASEF	Pathways	VM	esports	
Salvation Army	Engage	V		
IDRA	Engage	VM	multi	F
CyberTexas	Engage	VM	cyber	I
UP Partnership	Pathways			
Family Service	Pathways	VM	multi	I
SA Area Foundation	Engage	VM	multi	F
Hurd Foundation	Pathways	VM	multi	F
Kronkosky	Engage		esports	F
Alamo STEM	Pathways	VM	multi	I

Table 2.
Key program attributes seen with partners.

The most in-depth program is Boeing STEM Academy, a 12-session engineering design course. Middle school students learn engineering design principles and apply them to a project supported by Boeing and other mentors. Completing students are awarded laptops. Boeing STEM Academy has served 480 students. In 2024, 83 students from two Title I middle schools (grades 6–8) completed the program.

Program curriculum is strategically designed to cover a wide variety of interests, from robotics and aerospace to forensics and epidemiology. Students undertake their own projects, applying their knowledge to real-world problems. Technology is brought into the classroom to elevate the experience and deliver hands-on learning.

In a capstone project, teams use the engineering design process to develop an innovative product that addresses an important issue. Prior issues chosen by students include recycling and search-and-rescue operations. In a final showcase, students receive feedback and answer questions about their work.

Many students choose issues that resonate personally or spark unique interests, as demonstrated by their frequent selection of projects on food scarcity and pollution—both reflections of the challenges faced by the communities where many students live. One practical solution devised by students for combating food deserts involved the use of bus routes and a smartphone app to distribute fresh food. Some student teams ventured into topics not directly covered in the curriculum, such as human trafficking, indicating mature awareness and concern. Student teams have proposed impressive technological solutions. For example, a team proposed a keyword-activated GPS safety necklace to address safety and human trafficking.

The program culminates in a graduation ceremony where each student receives a certificate of completion, digital badge, and laptop. Families are invited to learn more about the experience. **Figure 4** shows pictures from a graduation ceremony.

Public school educators have reported notable benefits, including one teacher who specifically stated that the program has positively influenced their teaching. Families appreciate the opportunities provided to their children, and the laptop awarded

Figure 4.
Boeing STEM academy final presentations, graduation, laptop award.

equips the student with a tangible tool for their education. The program's ability to inspire was captured in the words of a seventh grader: "I LOVED this experience. It helped me learn new things and helped me better decide my future."

4.2 STEMclipse!

In October 2023 and April 2024, San Antonio experienced solar eclipses. Two eclipses in such close time proximity are exceedingly rare and presented a major opportunity for science engagement in the communities we serve. SAMSAT partnered with Port San Antonio, the University of Texas at San Antonio's (UTSA's) Department of Physics and Astronomy, the WEX Foundation, the Dee Howard Foundation, and Frost Bank for our event, named STEMclipse!. The Space Tourist, a local non-profit founded by a high school student, provided an interactive guest speaker experience. Southwest Research Institute's lead for the ultraviolet instrument on NASA's lunar reconnaissance orbiter joined the event. Capital Factory, a technology transfer organization in the Boeing Center, helped host. Councilwoman Dr. Adriana Rocha Garcia and her office supported the event.

Figure 5 shows pictures of the estimated 800 residents who attended, including students, parents, and other adults. Observations from the event included guests eagerly sharing new facts learned in a fun and friendly environment. One of our chapter co-authors lives in the community and grew up in the aftermath of Kelly AFB's closure. Our co-author contrasted the event with a perception in the community of being left behind by an overly academic approach that does not meet residents

Figure 5.
STEMclipse! event.

where they are, and associated feelings of disheartenment and exclusion. Asked to comment as a resident of the local community, our co-author shared:

> *Smiling, laughing, and excited for the eclipse, attendees eagerly shared new facts they had learned. The air was electric, and I watched older individuals who often felt left behind laughing and enjoying themselves alongside the crowd. Without the restrictions of a grade or pressure from an authoritative figure for perfection, people saw opportunity. The event fostered light-hearted exchange and discussion of new knowledge learned. Providing voice and a platform for curiosity to grow is integral for anyone, young or old, to learn in a way that encourages the pursuit of knowledge.*

4.3 SA Smart Mayor's Challenge

SA Smart: The Mayor's K-12 Smart City Challenge was founded in 2018 by SAMSAT's Chief Learning Officer (CLO), the Office of Mayor Ron Nirenberg, and Communities in Schools of San Antonio. The program just completed its seventh year of operation. It has served 1350 students since founding.

Inspiration for the program was the relative lack of action on climate change and the environment, witnessed firsthand by SAMSAT's CLO on a 2018 trip to New Delhi, India. He asked what could be done at home, building on his familiarity with the pillars highlighted by then-Councilman Nirenberg's first Mayoral campaign. The seven yearly themes have been transportation, sustainability, digital inclusion, food insecurity, water resources, transportation II, and environmental quality.

Each year, a challenge question is posed based on ideation by the prior year's student finalists. Teams of middle and high school students identify a local problem, perform research, and progressively build a pitch deck. Using a rubric prioritizing technical and market research, 10 or more finalists are chosen to present at the Mayor's Cup. **Figure 6** highlights the VertiGrow proposal from Clemens High School. The Clemens team won the high school bracket of the 2024 SA Smart Mayor's Cup.

Numerous partners support delivery, led by SAMSAT and the Office of Mayor Ron Nirenberg, with support from City of San Antonio departments, CPS Energy, and the San Antonio Water System. Partners have included Communities In Schools of San Antonio; Itron, Inc.; the local technology accelerator, Geekdom; the energy technology accelerator EPIcenter; the Digital Inclusion Alliance of San Antono; the San Antonio Area Foundation; and the Alamo STEM Ecosystem.

Figure 6.
SA Smart Mayor's cup poster presentation, final presentation, mentors.

Highlights from prior years include a deployed low-flow water filter distributed in partnership with the local food bank; 13 mentors attending the program's opening Competition Clinic; and Mayor Nirenberg touring student posters and interacting with student teams. While we cannot predict our ultimate impact, we believe we are helping raise the next generation of San Antonio leaders who will operate at the intersection of STEM, civics, and entrepreneurship.

4.4 R20 Premiere Esports

Port San Antonio identified esports as a strategic focus prior to the design and construction of its Innovation Center, now the Boeing Center at Tech Port. In parallel, SAMSAT explored esports programming, conducting a prototype event in partnership with Boeing Center staff. We were later contacted by a local school district, Southwest ISD, and challenged to create a citywide competition where students could compete against the other 16 ISDs in San Antonio.

The result is the R20 Premiere Esports League. Over 3 years, R20 grew to serve 300 students per month via in-person programming, using the model of the Network of Academic and Scholastic Esports Federations (NASEF).

The concept of video games in the K-12 education space is relatively new, with national online leagues like High School Esports League (HSEL) and PlayVS seeing major growth [24, 25] and NASEF having 3500 registered clubs in the U.S. as of February 2024 [26]. In a recent survey, 85% of teens aged 13–17 play video games [27]. R20 Premiere started with 87 students from 11 campuses, with the grand prize being an $8000 scholarship per student to St. Mary's University. The program has grown to serve 35 campuses.

Using the engagement of esports, we drive learning outcomes through the communication, critical thinking, and strategizing required in team games, and through students' experiences when running tournaments. SAMSAT observes that esports is often a student's first extracurricular connection in school, serving as the entree for a deeper school experience that can lead to education and career opportunities. **Figure 7** shows a preliminary round underway as an interview is conducted on the Boeing Center main stage, during the April 2024 finals.

Executing a large-scale esports event requires skills in IT, networking, event management, marketing, 3D and motion graphics, broadcasting, video production, and

Figure 7.
R20 grand finals: Preliminary round and stage interview.

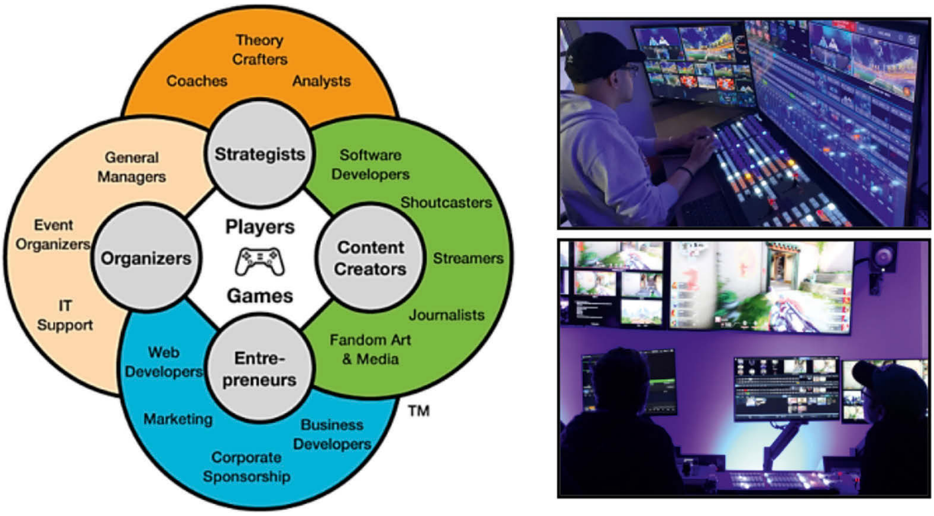

Figure 8.
NASEF model with R20 student intern examples [28].

business development. R20 events are run by college interns from education partners Texas A&M University-San Antonio (TAMUSA) and Alamo (Community) Colleges. Along the way, high school students see college interns in action. Training current and former collegiate competitors for the professional workforce is the hidden mission of R20. All R20 interns—100%, across 11 interns—have entered the workforce in each student's desired field of work.

As NASEF's affiliate, we use the NASEF club model for developing high school campus programs. Beyond the twentyfirst century skills of teamwork, communication, discipline and emotional regulation, scholastic esports highlights the importance of the support team. Broad student participation across disciplines is required. Each school has a charter with elected positions and specific duties. The NASEF four-sector graphic in **Figure 8** highlights the skills needed to run a club: strategists, organizers, content creators and entrepreneurs. From these four areas, one finds 18 downstream jobs from esports tournament participation [28].

5. Methods of measurement and self-evaluation

5.1 Overview

SAMSAT programs are evaluated through a variety of methods. We deploy a basic evaluation form. We collect event records with counts and demographics. In selected programs, we use research-based methods. Our goal is a set of inputs that are practical to collect and provide an overall picture of performance.

Our basic evaluation form is used across all programs, collecting quantitative and qualitative data. We invite first impressions, and also comments on learnings during a class. We request ratings on class organization and instructor performance. We invite ratings on whether students were given voice during the class, and whether education and career opportunities were highlighted. Results are reviewed weekly. We highlight positive feedback for reinforcement and critiques for evaluation and action. SAMSAT's standard evaluation form is found at www.samsat.org/eval.

Staff members leading events capture event records. Each record documents the funder (who paid for the event), client (who we served), number of students, gender and ethnicity demographics, and the number of teachers, parents and other adults served. We document the number of students attending Title I schools, a common U.S. measure for serving economically challenged students. From these data, spreadsheet formulas produce summaries by date range, client, and school, giving us real-time information about performance across programs.

We note that student counts are duplicated, meaning that a student attending multiple events is counted each time they arrive at a SAMSAT event. This approach enables consistency in data capture across all programs—staff capture data in the same way every time. The approach also provides a fair basis for comparison of programs that serve a large number of students once, versus programs serving a small cohort of students many times (in other words, inspiration-driven programs, versus engagement or pathway programs).

Selected programs require counts of unduplicated (unique) students, and those counts are performed within each program. We estimate our overall unduplicated count to be 50–60% of the unduplicated number of people served. A SAMSAT-wide unduplicated count of students or adults is impractical for multiple reasons, including privacy issues, multiple ISD systems, and the data alignment that would be required across programs. Also complicating such a count is the free access offered for all visitors to SAMSAT AREA 21, and the impracticality of associating a child visiting with family with the same child's record when visiting with a school.

Research-based methods are applied in selected programs, using both funder-specified methods, existing validated instruments, and instruments under development by SAMSAT. Among the measurements we take for funders are direct data on economic status, household size, and military affiliation. We have arranged for multiple in-person interviews between funders and program participants. We are collecting data from the STEM Career Interest Survey [29] to determine if selected programs increased student interest in STEM careers. We are developing the Character in STEM through Experiential Learning (CHISEL) [30] instrument to determine if STEM programming is helping develop character attributes in students. We note that many proposals include a literature review, a step which grounds funded programs in the practices, questions, and challenges identified in research and prior experience of the field.

5.2 Data examples and summaries

Table 3 summarizes our methods of measurement as described above. **Table 4** shares descriptive statistics from 2023 event records. **Figure 9** shares results from SAMSAT's standard evaluation. **Table 5** summarizes results from use of research-based instruments. Work with research-based instruments is ongoing and should be interpreted as preliminary.

5.3 Qualitative data

Qualitative data provides important context for evaluation. Our basic evaluation form is designed to invite first impressions at the top of the survey, before other questions can create bias in responses. In general, qualitative data helps protect against assumptions inherently found in quantitative instruments. The two types of data, taken together, form a more complete picture of SAMSAT's efforts.

Category	Description
Basic evaluation	Standard, simple evaluation form, with qualitative and quantitative questions, useful for all programs/participants.
Event records	Per event. Captures funder, client, attendance, demographics. Automatic rollup into real-time data.
Research-based	In selected programs, based on program-specific needs.

Table 3.
Methods of measurement.

Number of records (events)	711	Teachers	617
Male	14,642	Parents	792
Female	9799	Other adults	14,017
Non-binary	41	Total students	24,533
Gender not reported	51	Total adults	15,426
Title I + underrepresented	80.5%	Total	39,959
-	-	Daily average	109

Table 4.
2023 event record descriptive statistics.

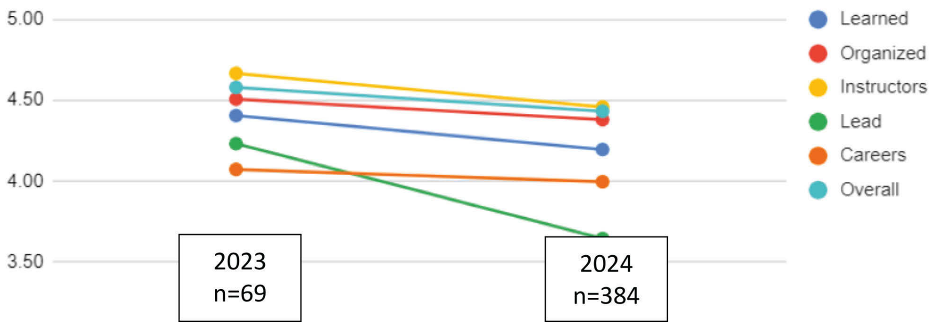

Figure 9.
SAMSAT standard evaluation results, 2023 and 2024.

Instrument	Purpose	Status
STEM Semantic Survey [29]	Are we changing students' view of STEM in programs?	675 pre and post surveys collected. Analysis pending.
Character in STEM through Experiential Learning (CHISEL) [30]	Does STEM programming build student character?	Preliminary evidence of impact on communications skills [30]. Validation of instrument pending.

Table 5.
Preliminary results from research-based instruments.

Figure 10.
SAMSAT basic evaluation: Qualitative question word cloud.

Figure 10 was generated from survey feedback on first impressions and on learnings during SAMSAT classes. The figure provides a quick visual summary of the kinds of topics found in feedback.

ChatGPT was used to analyze 453 responses dating back to June 2022, with results reviewed by the authors, compared to survey details, and revised. The review yielded these themes, mostly positive, but also highlighting areas to watch.

1. *Positive learning experiences*. Classes were generally fun and informative. Areas of learning highlighted were cybersecurity; general technology; digital safety and recognizing threats; engineering principles; building robots; exposure to modern technologies like 3D printing, robotics and artificial intelligence (AI); AI and self-driving cars; space exploration; and DNA.

2. *Learning about career opportunities and pathways* in cybersecurity, robotics, and aviation.

3. *Twenty first century skills*. Responses noted teamwork, collaboration, communication, and presentation skills.

4. *Activities that engaged*, for example, hands-on learning, student projects, Minecraft activities, and cyber card games.

5. *Curiosity*. Students' interest was piqued, especially regarding cybersecurity and its application in real-world scenarios.

6. *Friendly and organized staff*. A well-managed, welcoming environment.

7. *Excitement and enjoyment*: Expressed by students and parents.

8. *Desire for more duration and depth*: Selected participants expected more in-depth learning. A few participants expressed boredom or confusion regarding content. We note this aligns with anecdotal observation by staff regarding older and/or more advanced students.

9. *Curriculum questions*. Parents wished to know more about the curriculum and alignment with education standards, particularly in relation to cyber security and its relevance to local middle school coursework.

10. *Logistics and communications*. Selected participants made comments regarding how logistics or communications could be improved

5.4 Observations

The data shared above represents a significant effort by SAMSAT's staff. For example, 711 times in 2023, a staff member recorded statistics for an event. Establishing the methods, tools, habits and culture to collect this data has been an approximate three-year process, and fully establishing habits is an ongoing effort. Consistent focus on data by leadership is essential to achieve routine data capture and its near-real-time translation into formats that are useful and actionable.

The data presented illustrates why this is important. We believe the 711 events, 24,533 students served, and 39,959 people served represents a significant accomplishment for an organization of our size. Prior to systematic data capture, we did not know the number of teachers and parents served each year through our education programs. These data are essential to organizational development efforts. The data help us track our growth.

Regarding improvement, the data illustrates the imbalance we have between male and female students. While one particular SAMSAT program accounts for some of this result, we see that across all our programs, when students are self-selecting, more males are participating. This insight provides a target for improvement. We also see a mild reduction in satisfaction ratings. This may be due to broader and more consistent incoming evaluations, yet it is data to watch. In particular, it appears students are receiving fewer opportunities to lead and have their voice heard. We will focus on increasing these opportunities.

Our data is incomplete if it lacks qualitative context. Whether ratings rise or fall, the free form comments shared in evaluation help us know why. Lacking that context, any assignment of reasons may or may not be accurate. Quantitative information tells us what is going well, and what is not. Qualitative information also informs performance, and it helps us understand why good or bad outcomes are happening, and what responses might be effective.

6. Social-Emotional Learning

STEM programming is not regularly associated with Social-Emotional Learning (SEL). Yet we have observed how STEM experiences can contribute to the social and emotional health of students, both directly, and through development of twentyfirst century skills like the 4 Cs: communication, collaboration, critical thinking and creativity. These skills have wide application in the life of a student. A hands-on, team-based, interdisciplinary approach gives students opportunity to belong to a group, develop twentyfirst century skills, and develop self-efficacy regarding STEM topics and skills.

We see examples in multiple programs. In the R20 Premiere Esports League, we see students using esports as the entry point to school engagement, teamwork and accomplishment, with selected students leveraging the opportunity into education and career pathways. In the SA Smart Mayor's Challenge, students work in teams, develop 4 Cs skills, and see how they can make a difference in the challenges around them. Students likewise address local challenges in Boeing STEM Academy. In Kronkosky Mobile Esports, a research instrument under development showed an improvement in communication skills among participating students, with that finding related to the development of student character attributes [30].

Table 6 summarizes anecdotal observations regarding STEM programming and SEL. The 4 Cs column indicates the exercise of related skills. The belonging column

Program	4 Cs	Belonging	Comm.	Opportunity	Self-efficacy
21DISCOVERY	X	X		X	
R20 Premiere	X	X	X	X	X
SA Smart	X	X	X	X	X
Boeing STEM	X	X	X	X	X
Hurd/Boeing pathways	X			X	X
Kronkosky	X	X	X	X	X

Table 6.
Anecdotal observations of SEL in STEM programming.

indicates the opportunity to work in a team. Communication indicates the chance to exercise public communication skills. Opportunity indicates the highlighting of STEM opportunities. Self-efficacy indicates a deep enough opportunity for a student to discover that they can exercise a STEM skill successfully.

7. Takeaways

7.1 Strong platform

SAMSAT's decision to locate at Port San Antonio created a strong strategic platform. Port San Antonio is home to major aerospace, cyber and robotics missions, has key players in Boeing and Sixteenth Air Force, and applies an innovative, forward-thinking strategy that includes education as a core mission. Those building a STEM learning ecosystem should consider what location, key partner/s, and partner strategies provide the strongest platform for STEM learning.

7.2 Robust partner outreach

SAMSAT's partnerships include funders, in-kind providers, volunteer and mentor providers, and peer organizations on compatible missions. SAMSAT seeks win-win relationships, with the belief that voluntary partnerships tied to each organization's priority goals are most likely to sustain and grow. In building a STEM learning ecosystem, we recommend securing partners that meet these criteria.

7.3 Local priorities

SAMSAT's ties to local priorities gain the attention of leaders from K-12, academia, industry, government, and non-profits. In doing so, we align again to attributes that best attract in-kind resources, volunteers, mentors, and funding.

On a periodic basis, we observe how this choice manifests in K-12 schools in a very practical way. Many teachers have spouses or partners who work in the cybersecurity industry, far more than one would observe in other cities. A few teachers are retired cyber professionals engaged in a second career. Strictly based on anecdotal observation, we estimate that 75% of schools have a teacher who is either a former cyber industry professional or has a spouse or partner who is. This is an enabling situation for cyber programs with schools.

Local priorities include the identification of specific fields. They also include the long-term visions, strategic plans, and themes seen in local governments, industries, foundations, and media. When building a STEM learning ecosystem, organizations should identify local priorities as platforms for great learning experiences.

7.4 Design for relevance

Building on local priorities means making programs relevant. To choose a local priority, and then design and deploy programs that fail to make relevance central, misses the opportunity. Our programs prioritize hands-on engagement, student voice, student choice, and career professionals as speakers and mentors. Problem-, project-, and inquiry-driven pedagogy, including PBL, are our guides. We observe a virtuous cycle when designs are found relevant by our clients and students. Relevant designs bring more opportunities. In the short term, this takes the form of brand awareness and repeat business. In the medium and long term, students become near-peer mentors, and then industry mentors and volunteers. Those building a STEM learning ecosystem should design learning experiences based on local priorities, and they should use tools and techniques that draw out relevance.

7.5 Program artifacts

SAMSAT brings focus to student creation of artifacts, and on capturing program artifacts. Artifacts include pictures and videos of programs; quotes from students, teachers, and adults; and student deliverables including presentations, posters, tangible products, etc. In fact, in this chapter, the pictures shared are artifacts intentionally collected by our staff. In our experience, the importance of collecting and assessing program artifacts must be communicated by leadership, kept simple, with priority given to ongoing and sustained collection, and labeling and storing in ways that they can be found when needed.

SAMSAT observes multiple benefits. The focus reminds us constantly to give students ample opportunity to create during programs. This focus keeps us tied to underlying philosophies of constructivism and constructionism that guide our work—it makes the choice of those philosophies practical. Artifacts themselves become tools for grantmaking and development, advancing our overall mission. Those building a STEM learning ecosystem should bring significant focus to the creation, capture, review, and use of program artifacts, both those created by students, and those captured by team members.

7.6 Practical evaluation

Over years, SAMSAT has created a system of data capture and evaluation that provides useful data to leadership, while also being practical to capture. SAMSAT's methods are: (1) a standard evaluation form that works across all programs, participants, and settings; (2) diligent capture of attendance information; (3) diligent capture of artifacts; and (4) consistent review and response to results. While SAMSAT has not reached the point where rigorous and advanced research methods (for example, validated instrument-based studies) are applied across all programs, such methods are used in selected programs, and these methods are being more broadly integrated.

Consistent, real-time capture of data is not easy; however, crisis projects to retrieve data in hindsight are especially difficult. Organizations building a STEM learning ecosystem should bring focus to real-time capture of practical data that helps the organization assess results, pursue more resources, and highlight impact.

8. Conclusion

In this chapter, we shared a qualitative description of SAMSAT's work building a multisector STEM learning ecosystem. We shared SAMSAT's context, approach to development, and pedagogies for instruction. We learned how SAMSAT's work is rooted in the story of the former Kelly Air Force Base and Port San Antonio. We shared models that inform SAMSAT's work, including the STEM Technopolis Model, STEM learning ecosystems, and the NASEF model for esports program development. We highlighted the importance of partnerships, and how partners both contribute to SAMSAT's work and benefit from our joint efforts.

We demonstrated how these models, approaches and partnerships manifest in four programs: Boeing STEM Academy, STEMclipse!, the SA Smart Mayor's Challenge, and the R20 Premiere Esports League. We shared SAMSAT's practical-yet-persistent approach to self-evaluation and measurement, and places where SAMSAT deploys research-based methods of measurement and evaluation. We explored the relationship of STEM programming to social-emotional learning. We identified takeaways: having a strong platform, building robust partnerships, building on local priorities, designing for relevance, capturing program artifacts, and performing practical measurement and evaluation. Various tables highlighted our partnerships, how our partnerships align with key SAMSAT approaches, our chosen methods of measurement and evaluation, and ties to social-emotional learning.

SAMSAT has a responsibility to serve those who have not fully participated in our city's growth, an opportunity that can transform students, families and communities while also strengthening our city's presence on the global stage. By following the practices described in this chapter, SAMSAT has built, sustained and grown programs. We encourage readers to seek their own context, identify local priorities, identify partners, adopt modern pedagogies, collect and use data, and design programs of relevance and inspiration for the students, families and communities they serve.

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Chapter 7

Examining Access and Inclusion in STEM Fields in Higher Education: Digital Learning Environments, Personalized Learning, and Institutional Change to Advance Educational Opportunity

Kimberly Cook-Chennault

Abstract

The use of digital educational games and virtual laboratories as supplemental instructional tools has grown over the last several decades in most STEM disciplines. Yet, how diverse student populations interpret, experience, and value these technologies is not fully understood. Contradictory results across studies suggest effectiveness may depend on student identity factors (e.g., race, gender, socioeconomic status, culture), disciplinary context, and classroom integration. Additionally, personal reflections and auto-ethnographic experiences of neurodivergent faculty illustrate the complexities of navigating higher education where systemic biases related to race, gender, and disability can impede access and inclusion. By connecting evidence from multiple studies, this chapter explores ways in which digital tools and equitable institutional policies can address the barriers often faced by marginalized students and faculty. Recommendations are provided for designing personalized learning virtual and in-person environments, implementing universal design principles, and cultivating policies that promote inclusivity for all STEM learners in higher education.

Keywords: digital serious games, game-based learning, technology acceptance model, human-computer-game interaction, motivational learning

1. Introduction

1.1 Rationale for examining STEM access and inclusion

In the United States, Science, Technology, Engineering, and Mathematics (STEM) fields have long grappled with systemic inequities in representation in career pathways and institutes of higher education. National statistics underscore that women, African American/Black, Latiné, Indigenous, first-generation, and socioeconomically disadvantaged students continue to be underrepresented in many STEM disciplines [1–3]. Racial and social identity constructs have dictated the infrastructure of the US' caste system of educational *access* for centuries [4] and continue to play a pivotal role in *how* the US provides (or fails to provide) opportunities to learn, excel, and achieve in institutes of higher education. Considering the prohibition of segregation in schools and public facilities was signed into law in Brown v. the Board of Education (1954) and Civil Rights Act of 1964 [5] some argue that Americans have collectively come a long way. However, several decades of scholarship note that institutional practices and biased educational cultures contribute to lower representation and "success" among these groups in STEM disciplines [6, 7]. These *chilly and normalized environments of educational exclusion* have been most noted and rigorously studied in STEM disciplines in US institutes of higher education [8, 9], despite the articulated need for more STEM professionals [10, 11]. STEM professionals are essential to the US in maintaining a sustainable economy, which is connected to its technological capabilities. Thus, STEM professionals are critical to the US' national security [12–14]. Acquisition of STEM degrees and the careers that follow, provide meaningful translatable skills (e.g., critical thinking, problem-solving, data analysis, computational literacy, engineering design, technical communication, and innovation) and legitimate pathways for individuals to achieve social mobility—often transcending that of their parents, leading to more economically secure, fulfilling, and impactful lives [4, 15].

Inequitable funding for gifted programmatic courses (e.g., Advanced Placement, AP courses) [16], exposure to STEM fields and extracurricular activities [17], access to credentialed instructors, socially conscious academic support, and role models have often limited the number of marginalized students prepared to enter and/or graduate from STEM degree programs, along with deficit-based approaches to teaching/evaluating STEM academic performance. These things lead to in lower BS graduation rates of these groups in STEM in comparison to those in liberal arts programs in the US. These barriers are not only evident in enrollment and graduation numbers, but also manifest in differential access to resources, mentorship, and opportunities for professional growth [6, 18–21] for STEM faculty members in the academia. For example, inequitable funding, access to professional support, and mentorship continue to disproportionality affect these groups seeking STEM careers in the academy. Low funding rates of marginalized faculty are found across all US federal funding agencies, e.g., the National Science Foundation, Department of Health and Human Services, Department of Defense, Department of Energy, National Aeronautics and Space Administration, Department of Agriculture, National Institutes of Health [21–24], which fund over 90% of all STEM research and development at US colleges and universities [21–24].

Scholarly work has also begun to illuminate the "invisible" challenges faced by neurodivergent students and faculty—such as individuals with autism, ADHD, dyspraxia, and dyslexia, who encounter hidden obstacles due to entrenched, normative academic practices and environments [25–27]. Recently, new scholarship has begun to shed light on how faculty and students whose identities exist at the intersection of race, gender, and neurodivergence may experience unique biases that are more pronounced than the populations whose identities are not intersectional [28, 29].

Ensuring that all individuals have equitable access to quality education and career advancement in STEM aligns with the *Sustainable Development Goal 4 (SDG 4)*, which is part of the United Nations' global commitment to providing *inclusive and equitable quality education and promoting lifelong learning opportunities for all* [30].

While SDG 4 is often discussed in the context of K-12 and global education access, it is equally critical in higher education, particularly in STEM, where structural barriers continue to disproportionately limit participation and success for historically excluded groups to a higher degree than in liberal arts fields [31]. Addressing inequities in STEM education is not just about increasing representation but also about dismantling systemic exclusionary practices embedded in institutional policies and norms that define the promotion and evaluation of professional merit, and access to educational and professional development resources.

One way to mitigate these inequities and expand affordable, lifelong learning opportunities is through personalized learning approaches that leverage digital educational tools, flexible curricula, and adaptive learning pathways. These innovations may provide unbiased, non-judgmental, anti-deficit-based STEM education [32, 33] by accommodating diverse learning needs, reducing traditional barriers to entry (cost, time, location), and supporting nontraditional students, such as working professionals, caregivers, veterans, and adult learners, who seek to complete or advance their STEM education often through remote and virtual landscapes. Personalized learning platforms can also create judgment-free environments that foster engagement and success for neurodivergent students and those from marginalized backgrounds, enabling them to thrive without conforming to rigid, exclusionary academic norms. This chapter explores how integrating personalized learning with institutional reforms can enhance equity, improve retention, and create more inclusive pathways for students and faculty to succeed in STEM.

1.2 Overview of the chapter

This chapter, titled *Examining Access and Inclusion in STEM Fields in Higher Education*, reimagines how access and inclusion can be enhanced by examining the intersection of race, gender, and neurodivergence. Drawing on my previously published work, decades of studies and reports from notable scholars from around the word, and the National Academy of Engineering's Grand Challenge to *Advance Personalized Learning* [34], I argue that digital formal and informal educational tools, such as serious digital engineering educational games and virtual laboratories—present promising avenues for providing access to STEM to marginalized communities using mechanisms that can reduce role strain and cognitive load. However, their potential can only be fully realized if these tools (and the environments in which they are employed) are critically designed and implemented to consider the individual's unique social, cultural, and neurological identities [35–38], which also necessitates addressing and minimizing deeper systemic biases in institutional policies and campus cultures in the educational system [6, 39–43].

The chapter is structured to first explore the multifaceted nature of diversity and marginalization in STEM higher education and how it relates to the use of digital engineering education tools used within classrooms. It reviews persistent barriers for racially and ethnically minoritized groups, the compounded challenges posed by intersecting identities (e.g., race, gender, and neurodivergence), and the specific invisibility of neurodivergent identities in academic contexts. Next, the focus shifts to digital educational tools, chronicling their evolution in STEM instruction, examining mixed findings regarding their effectiveness and engagement, and highlighting the promise of universal design principles in creating personalized learning opportunities.

Building on this foundation, the chapter then discusses how these digital tools can be leveraged to enhance access and inclusion. In particular, it examines the importance of real-time feedback and personalized learning pathways. It considers how the thoughtful design of these tools, such as, one that integrates diverse perspectives, can help mitigate cognitive load and role strain (the stress experienced when fulfilling multiple, often conflicting, social or professional roles [44, 45] among students and faculty.

The subsequent section examines the challenges of navigating a predominantly *neurotypical academic ecosystem*, the role of *personalized learning tools in reducing cognitive and emotional load*, and the need for *institutional policy reforms* to foster inclusion. It discusses *masking and camouflaging among neurodivergent individuals*, explores how *digital interventions can enhance accessibility*, and highlights *policy changes necessary to mitigate role strain and ensure equitable evaluation of knowledge, impact, and expertise in STEM academia*. Together, these discussions provide a comprehensive framework for *bridging systemic inequities and advancing a more inclusive future in STEM education*.

2. Diversity and marginalization in STEM higher education

STEM fields worldwide have long grappled with systemic inequities that hinder the success of many students and faculty. These challenges are multifaceted, ranging from historical underrepresentation of marginalized racial groups that was shaped during the US' infancy, such as, legalized bans on educating Black enslaved populations [46–48]. These and cultural norms later evolved into discriminatory practices and educational segregation that prohibited Black/African American students from attending colleges and universities [46–48]. Later, once, Black/African Americans were allowed access to institutes of higher education, they were often met with racialized climates of intimidation and violence on college campuses in the US. These interactions and incidents aimed to disenfranchise racially marginalized/minoritized groups from participating and graduating from institutes of higher education [49–55]. This long and complicated legacy of ongoing institutional practices disadvantage certain groups, while perpetuating and normalizing rigid caste systems in the educational system [15, 56, 57].

2.1 Persistent barriers for racially and ethnically minoritized groups

Several scholars have discussed how institutional practices and biased educational cultures contribute to lower representation and success among women, African American/Black, Latiné, and Indigenous individuals [6, 58], in STEM disciplines in higher education. For example, several studies have documented how legacy policies, such as inequitable distribution of funding and limited access to academic support that have resulted in measurable disparities in graduation rates and faculty retention [3, 21, 41, 59–63]. In addition, recent media narratives in the United States have at times, challenged the value of diversity, equity, and inclusion (DEI) initiatives, arguing that such efforts may compromise academic standards [64–66]. However, empirical evidence consistently shows that DEI initiatives not only improve academic outcomes but also foster innovation and excellence [1, 2, 61, 67].

2.2 Intersectionality of race, gender, and additional identities

Intersectionality, a term coined by Crenshaw [68, 69], describes how overlapping social identities interact to produce complex, layered experiences of marginalization that cannot be fully understood by examining each identity in isolation. In the context of STEM higher education, for instance, a Black woman often encounters both racial and gender biases simultaneously, resulting in challenges that are more severe than those experienced by individuals facing only one form of marginalization [6, 68]. These groups are also often not considered and overlooked when engineering education tools and systems are designed and implemented [59, 70–72].

Recently, a handful of scholars have examined the ramifications of individuals existing at the intersection of multiple identities beyond race and gender, such as neurodivergence (encompassing neurological traits such as autism, ADHD, and dyslexia) as a part of their identity. They concluded that under these compounded circumstances, the systemic biases embedded in academic environments become even more pronounced [28, 29, 73], despite the added value that these individuals may bring to STEM disciplines. This point is affirmed as many STEM communities being to recognize notable scholars of the past who may have been considered as possessing neurodivergent traits in today's society, such as Albert Eistein (theoretical physicist) [74, 75], Isaac Newton (physicist and mathematician) [76], Alan Turing (mathematics and computing) [77]. To counteract the promotion of negative media and normalized misrepresentation of the contribution of neurodivergent individuals to society—scholars and online media movements within the US have promoted the ideology of neurodivergent traits as a natural variation in cognitive functioning. These scholars reframe neurodivergent traits instead as a valuable aspect of human diversity [78]. Nevertheless, in practice, neurodivergent individuals often encounter "invisible" barriers in educational settings that are predominantly structured around neurotypical norms [25, 27]. Addressing these challenges is critical not only for ensuring inclusive, high-quality STEM education—upholding the commitments of the United Nation's Sustainable Development Goal 4 (Quality Education) by providing adaptive learning environments for all, but also facilitate the reduction of entrenched societal disparities in line with Sustainable Development Goal 10 (Reduced Inequalities). By designing STEM environments that actively celebrate and support neurodiverse perspectives through inclusive pedagogies, tailored digital tools, and equitable institutional practices, educational institutions can dismantle long-standing inequities, promote lifelong learning, and foster innovation, thereby contributing to a more inclusive and sustainable society [30].

For example, my work has documented instances where neurodivergent faculty of color encounter not only overt racial and gender biases but also subtler forms of marginalization that stem from expectations to conform to neurotypical behavioral norms. These expectations force individuals to mask or camouflage their authentic selves—a phenomenon that significantly increases cognitive load and role strain [28, 29, 79, 80]. Standard diversity initiatives that focus solely on one axis of identity (e.g., race or gender) risk overlooking the compounded challenges faced by those who exist at the intersection of multiple marginalized identities. As several scholars have noted [21, 71, 81, 82], without an intersectional approach, institutional reforms may fail to address the full spectrum of barriers, leaving neurodivergent individuals, particularly women of color, without the necessary support systems to thrive in STEM fields.

Furthermore, this compounded marginalization can have measurable consequences for professional development and career advancement. Studies indicate that the combined pressures of racial, gender, and neurodivergent biases can lead to lower retention rates, diminished access to resources, and increased instances of burnout among faculty and students [25, 27]. In contrast, when institutional policies and interventions are designed with an intersectional lens that integrates insights from both empirical studies and autoethnographic narratives, they are better positioned to create more inclusive academic environments that recognize and support the full range of identities present in STEM.

Thus, an intersectional framework is critical for understanding and addressing the multifaceted challenges in STEM higher education. By considering the interplay of race, gender, and neurodivergence, educators and policymakers can develop more comprehensive strategies to dismantle systemic barriers and foster an environment where all individuals have the opportunity to succeed.

2.3 Neurodivergent identities: Visibility vs. invisibility

Neurodivergence refers to the idea that variations with cognitive functioning, such as autism, ADHD, dyslexia, dyspraxia, dyscalculia, and dysgraphia, which are natural differences in the human brain rather than deficits [78]. Despite being “invisible” in many traditional educational assessments, these differences profoundly affect how individuals engage with academic practices. Research shows that normative academic environments tend to privilege neurotypical behaviors, leaving neurodivergent students and faculty to shoulder additional challenges such as increased role strain and cognitive load [25, 27, 32]. This hidden marginalization is compounded when neurodivergent individuals also belong to other underrepresented groups, further underscoring the need for approaches that integrate personalized learning tools with broader institutional reforms.

3. Digital educational tools: Games and virtual labs

Digital educational tools—ranging from serious games to virtual laboratories—have become an increasingly vital component of STEM instruction worldwide, as educators recognize that these tools align with Universal Design for Learning (UDL) and offer personalized learning pathways for diverse learners [83], serious learning games, virtual online laboratories [84, 85], and simulations have been shown to benefit both neurotypical and neurodivergent learners by providing multiple means of engagement, representation, and expression [83]. In response to evolving technological capabilities and the rapid expansion of remote and hybrid learning [83], educators have increasingly integrated these tools not only to supplement traditional lectures but also to foster active learning and provide immediate, personalized feedback. Many of these advancements in curriculum, supplemental materials, and student engagement methods address findings from the *United Nations Disability and Development Report*, which underscores the importance of inclusive educational approaches to support individuals with disabilities [30].

A growing body of research demonstrates that digital and online educational tools can deliver on the promises of UDL for neurodivergent learners in multiple ways. Game-based learning, in particular, has been identified as a powerful tool for scaffolding executive functioning skills, such as working memory, cognitive flexibility, and inhibitory control, which are often areas of difficulty for neurodivergent students [86]. Adaptive game-based learning environments incorporate embedded scaffolds that support metacognition and allow students to externalize their thinking processes, ultimately promoting persistence in STEM-related problem-solving [32, 86]. For example, games like *Zoombinis* and *NumberFactory* integrate structured supports that help neurodivergent learners develop systematic testing strategies, recognize patterns, and refine their decision-making approaches [86].

There is no one-size-fits-all approach to leveraging digital, electronic, and multimedia learning tools for STEM education for individuals with neurodivergent traits. However, studies indicate that game-based learning can enhance engagement by offering immediate, adaptive feedback while supporting students in developing problem-solving skills and computational thinking [83]. Gregg et al. [87], for example, found that virtual mentoring, digital voice communication, and text-based communication platforms, when combined with online learning and training, provided multiple ways for neurodivergent students to engage with STEM concepts. These platforms also allowed students the flexibility to decide how they would be represented (e.g., avatars) in digital learning environments and provided them with the necessary processing time to respond to inquiries.

Project-based learning (PBL) has also emerged as an effective instructional method for engaging neurodivergent learners in STEM. Unlike traditional instructional approaches, PBL emphasizes real-world problem-solving and allows students to work at their own pace while leveraging their individual strengths [83]. Research suggests that PBL fosters motivation by embedding learning within meaningful, real-life contexts and promoting autonomy in learning [83]. This approach aligns well with UDL principles, as it provides multiple means of action and expression, catering to diverse cognitive profiles [83]. Studies show that project-based approaches particularly benefit neurodivergent students by allowing them to engage with STEM subjects in ways that align with their strengths, such as pattern recognition and problem-solving through hands-on experiences [88]. Furthermore, a recent study found that PBL in engineering education increased persistence and retention rates for students with neurodivergent traits by emphasizing flexibility in assessment and allowing students to demonstrate knowledge in ways that best suit their cognitive strengths [88].

Additionally, the use of digital and computational tools within PBL contexts enables neurodivergent learners to engage in inquiry-based learning while receiving embedded supports, such as structured feedback, real-time assessments, and scaffolded instruction [89]. Research has demonstrated that these methods can increase motivation and reduce anxiety by shifting the focus from rigid, high-stakes assessments to iterative learning experiences that emphasize mastery and process over performance [89].

Furthermore, integrating game-based and project-based learning strategies can increase the accessibility of computational thinking for neurodivergent students. Studies have shown that computational thinking practices help students develop systematic problem-solving skills critical for STEM disciplines [83]. For instance, Microsoft has developed coding camps specifically for students with autism to strengthen collaboration, communication skills, and programming abilities, demonstrating how targeted interventions can bridge the gap in STEM education [83].

This section examines the background of digital tools in STEM, discusses their mixed effectiveness and engagement outcomes, and explores how principles of Universal Design for Learning can open pathways for personalized learning.

3.1 Background and growth of digital tools in STEM instruction

Over the past few decades, STEM disciplines have witnessed a significant evolution in instructional technology. Early digital tools were often limited to computer-based tutorials; however, the last twenty years have seen the emergence of interactive serious games and virtual labs that simulate real-world experiments and problem solving. Research [84, 90, 91] has demonstrated that when properly integrated into engineering curricula, such tools can facilitate experiential learning and reinforce core technical concepts. The COVID-19 pandemic further accelerated the adoption of these technologies as institutions worldwide pivoted to remote learning environments [92, 93]. As a result, digital educational tools now play a dual role: they extend access to high-quality instruction and offer dynamic, real-time feedback mechanisms that are critical for developing student competencies in STEM fields [36, 94–96].

3.2 Effectiveness, engagement, and contradictory findings

The promise of digital tools in enhancing student learning outcomes is widely recognized; yet the research presents a complex and sometimes contradictory picture. Studies have shown that serious games and virtual labs can boost engagement and facilitate deeper conceptual understanding by providing immediate feedback and adaptive challenge levels [35, 94, 96, 97]. However, not all findings are uniformly positive. Some investigations note that the effectiveness of these tools is often limited by factors such as insufficient alignment with course content, suboptimal user interface design, and the failure to account for diverse learner backgrounds [35, 36, 94, 98, 99]. Moreover, while digital tools have the potential to address the needs of various groups—including neurodivergent students—their benefits may not be fully realized if the design does not consider the perceptions, strengths, and challenges of these learners [25]. For instance, Cook-Chennault's exploration of engineering education digital games found that while many engineering disciplines use these tools to engage many learners; their potential to reduce cognitive load and enhance learning is contingent upon addressing underlying game design and strategies for implementation within a classroom environment that must be inclusive and student centered [35, 36, 94].

3.3 Incorporating universal design: Personalized learning opportunities

A growing body of research advocates for the adoption of Universal Design for Learning (UDL) principles to overcome the limitations of traditional digital educational tools. UDL is defined as an educational framework that calls for the design of flexible learning environments which accommodate a wide range of learner differences, including those related to neurodivergence [100–102]. By integrating UDL into digital tool design, educators can create personalized learning environments that not only allow all learners to access content in multiple ways but also provide targeted support for both strengths and areas of difficulty.

For neurodivergent learners, such as individuals with ADHD or autism, (conditions encompassed under the term *neurodivergence*), UDL principles are especially beneficial. These approaches facilitate environments where learners can engage deeply with content through hyperfocus on their areas of strength, while simultaneously receiving immediate, non-judgmental feedback on areas needing improvement. For example, students with ADHD might typically ask many questions that can be misinterpreted or critiqued in conventional classroom settings; in contrast, virtual learning environments designed with UDL principles serve as judgment-free zones where inquiries are welcomed and addressed promptly [93, 101]. Such supportive digital environments not only reduce the cognitive and emotional burden associated with masking or camouflaging their learning styles but also empower neurodivergent individuals to excel and make meaningful contributions to advancing interdisciplinary knowledge.

4. Leveraging digital tools for access and inclusion

Digital educational tools—such as serious educational games and virtual laboratories—offer promising avenues to reshape access and inclusion in STEM higher education. When these tools are designed and implemented in ways that align with Universal Design for Learning (UDL) principles and intersectional frameworks, they can help create personalized learning environments that not only provide real-time feedback and adaptive learning pathways but also acknowledge and address the diverse needs of all learners. This section discusses three key strategies for leveraging digital tools to advance access and inclusion.

4.1 Real-time feedback and personalized learning pathways

Digital interventions have the unique capacity to provide immediate, actionable feedback that helps students monitor their understanding and progress as they engage with complex concepts. Serious educational games and virtual labs incorporate adaptive challenge levels and instant feedback loops that empower learners to adjust their strategies in real time [90, 91, 103]. Such dynamic responses promote self-regulated learning and facilitate personalized learning pathways—allowing students, particularly those with neurodivergent profiles, to focus on their strengths while receiving supportive guidance for areas needing improvement [102]. For example, virtual labs that permit iterative experimentation without the fear of immediate failure create judgment-free zones where students with ADHD can ask questions freely and explore problem-solving strategies at their own pace [95, 98, 104]. This approach is critical because traditional classroom settings can sometimes inadvertently penalize behaviors common among neurodivergent learners [25, 28, 105].

4.2 Designing for diverse perspectives: An intersectional approach

Digital tools have the potential to level the playing field by integrating diverse cultural and personal perspectives into their design. An intersectional approach recognizes that learners bring a variety of lived experiences—shaped by race, gender, and neurodivergence—to the educational environment [21, 69–71, 73, 106, 107]. When digital interfaces incorporate culturally relevant visuals, language, and real-world examples, they validate the experiences of underrepresented groups and encourage broader participation [90, 91, 94]. For instance, tailoring game narratives to reflect diverse role models and authentic contexts can help marginalized students see themselves as active contributors in STEM [82]. This strategy not only improves engagement but also reduces the likelihood that students will feel alienated by materials that may otherwise be steeped in narrow, neurotypical, masculine perspective.

4.3 Beyond the technology: Faculty support, training, and policy

While digital tools can create innovative learning environments, their effectiveness depends on robust support structures at the institutional level. Faculty training, proactive diversity, equity, and inclusion (DEI) initiatives, and transparent policies are essential to maximize the benefits of these technologies [85, 90, 91]. Institutions that invest in comprehensive training programs ensure that educators understand not only how to use digital tools effectively but also how to adapt them to meet diverse learner needs. Moreover, policy reforms that emphasize equitable evaluation and promotion practices foster a culture where inclusive teaching strategies are recognized and rewarded [108, 109]. Embedding digital tools within a broader framework of institutional support can help mitigate role strain and bias, ultimately providing all students and faculty with an equitable opportunity to succeed.

4.4 Expanding access to advanced STEM learning tools

In addition to personalizing learning, digital educational tools democratize access to advanced STEM experiences. Virtual labs and game-based learning environments enable students from under-resourced institutions or remote areas to engage with complex experimental practices [98, 110–112], sophisticated equipment [111, 113], and advanced protocols/algorithms [114, 115] that are typically available only in well-funded university research laboratories [116, 117]. These platforms provide a safe and controlled learning space where untrained students can explore high-risk experiments without the hazards of operating real laboratory equipment or handling dangerous materials [118, 119]. By bridging geographical and financial gaps, these digital tools not only enhance learning outcomes but also contribute significantly to a more equitable and inclusive STEM education landscape.

5. Finding space for students and faculty in a neurotypical academic ecosystem - Can personalized digital tools level the playing field?

Traditional academic settings often enforce a narrow standard of "normalcy" that privileges neurotypical behaviors. For many neurodivergent individuals—particularly faculty and students who also belong to racially or ethnically minoritized groups—the need to "mask" or "camouflage" one's authentic self in order to gain acceptance imposes a heavy cognitive and emotional burden. In contrast, personalized digital tools, when designed with principles of Universal Design for Learning (UDL) and an intersectional lens, can provide alternative spaces that not only accommodate diverse learning needs but also foster genuine engagement and empowerment.

5.1 Understanding role strain in STEM academia

The Theory of Role Strain, as originally proposed by Goode [44], posits that every organization is characterized by a "quilted" social culture held together by various role strains—that is, the cognitive, emotional, physical, and mental challenges individuals experience when trying to fulfill their assigned roles. In academic settings, these strains arise not only from the intrinsic demands of teaching, research, and service but also from the additional pressure to conform to normative (often neurotypical) expectations. Complementing this view, Merton [120] introduced the concept of "role bargains," wherein individuals attempt to negotiate or select roles and interactions that minimize the strain they experience.

In the context of STEM higher education, role strain is manifested in the everyday experiences of faculty and students who are expected to meet rigid standards. For example, marginalized faculty and neurodivergent students often must expend extra cognitive and emotional energy to mask or camouflage their authentic behaviors in order to be seen as "acceptable" within the institution [28, 121, 122]. This additional burden can reduce the mental resources available for creative problem solving, teaching, and scholarly engagement—thus hindering their overall success and well-being. Institutional structures and evaluation practices, which rely heavily on quantitative and subjective measures of performance, may inadvertently reinforce these pressures [123, 124].

By understanding role strain in this light, we can better appreciate the value of designing digital educational tools and institutional policies that reduce these hidden burdens. Such tools, when coupled with transparent and equitable institutional practices, have the potential to alleviate role strain and support a more inclusive academic ecosystem.

5.2 Masking and camouflaging: Understanding the concepts

Masking and camouflaging are strategies that neurodivergent individuals often use to hide traits that diverge from neurotypical norms. According to [28, 79, 80, 121, 122, 125], masking involves suppressing behaviors—such as stimming or atypical communication patterns—that may be perceived as "different," while camouflaging entails consciously imitating neurotypical behaviors (e.g., maintaining eye contact or limiting the number of questions asked) to blend into the academic environment. *Stimming*, is a term that is used for self-stimulatory behaviors, which are repetitive or rhythmic behaviors that individuals, particularly neurodivergent people, engage in as a way to self-regulate emotions, process sensory input, or maintain focus [79, 125]. These behaviors can include hand-flapping, rocking, spinning, tapping, repeating words or phrases (echolalia), or using objects in repetitive ways. While often associated with autism, stimming is also observed in individuals with ADHD, anxiety, and other neurodivergent conditions [79, 122, 125]. Although these tactics may initially facilitate access, they are associated with a significant increase in cognitive load and role strain [121, 122, 126]. The mental energy expended in constantly monitoring and modifying one's behavior can detract from academic focus and professional growth.

5.3 Cognitive and emotional load in academic spaces

The constant pressure to conform to rigid, neurotypical standards result in elevated cognitive and emotional load [112, 127]. Cognitive Load Theory posits that working memory is limited, so the additional demands of masking deplete the mental resources available for processing academic content and engaging in creative problem-solving [112, 127]. Other studies [25, 28, 40, 122, 128, 129] have shown that the cumulative effect of masking not only increases anxiety but also hinders genuine participation in collaborative academic activities. In environments where neurodivergent behaviors are penalized or misunderstood, this strain can manifest in burnout, reduced job satisfaction, and diminished opportunities for advancement [27].

5.4 Linking digital tool engagement to classroom experiences

Digital educational tools offer an innovative alternative to traditional classroom settings that often demand conformity. Platforms such as virtual laboratories and serious educational games provide dynamic, judgment-free zones where neurodivergent students can engage more freely. When integrated with UDL principles, these digital environments allow for real-time feedback and adaptive pathways that cater to each learner's strengths. For example, a student with ADHD—who might typically be chastised for asking numerous questions in a conventional classroom—can thrive in a virtual setting where inquiry is encouraged and answered without the risk of negative evaluation [102]. Similarly, faculty members who face role strain due to the pressure of masking can benefit from digital tools for training or those facilitate collaboration and allow their expertise to be recognized without the constant need for camouflaging [28].

Digital platforms not only support personalized learning but also democratize access to advanced STEM experiences. They offer a controlled environment for experimentation, enabling learners from under-resourced areas or institutions to interact with complex experimental practices, high-end equipment, and advanced protocols that would otherwise be inaccessible [116, 117]. Such environments are particularly beneficial for students and faculty who require a non-judgmental space to explore and develop their competencies without the stigma associated with neurodivergent behavior.

5.5 Evaluating safe spaces through innovative assessment instruments

Emerging assessment instruments offer promising means to evaluate the effectiveness of these digital "safe spaces." For instance, the Student Perceived Value of an Engineering Laboratory (SPVEL) assessment instrument [90, 91, 95] has been successfully applied to measure engagement, learning gains, and user satisfaction in both virtual and in-person engineering laboratory environments. Such instruments capture both quantitative metrics (e.g., real-time feedback, cognitive load, and performance data) and qualitative insights (e.g., user narratives and reflective feedback) to provide a holistic picture of inclusivity and accessibility. Integrating these instruments with established models, such as the Technology Acceptance Model [130, 131] and Universal Design for Learning frameworks [132], can further validate digital interventions designed to reduce the burdens of masking and role strain. Recent work by Bolliger and Wasilik [133] and Means et al. [134] has demonstrated that well-designed assessment tools can drive iterative improvements in digital educational platforms, ensuring that they remain adaptive to the diverse needs of learners.

6. Institutional policy and environmental change

Effective change in STEM access and inclusion requires more than innovative classroom practices and digital learning tools—it demands a transformation of institutional policies and academic cultures. This section examines how entrenched norms and opaque evaluation practices amplify role strain and marginalization, and it outlines strategies for equitable faculty evaluation and for fostering an inclusive academic environment.

6.1 The role of institutional norms in amplifying role strain

Institutional practices and biased educational cultures contribute to the lower representation and success of marginalized groups. As Aguirre [6] outlines, traditional tenure and promotion systems—with their heavy reliance on quantitative metrics and subjective evaluations—often favor those who conform to dominant, neurotypical standards. For example, several researchers discuss how existing evaluation criteria can overlook the multifaceted contributions of faculty of color and neurodivergent scholars [47, 106, 123, 135], thereby increasing the cognitive and emotional load required to navigate these systems. Ambiguous policies and hidden curricula [47, 106, 123, 135] force marginalized faculty to expend extra effort to decipher institutional expectations, reinforcing a cycle of role strain and exclusion.

6.2 Strategies for equitable evaluation and promotion practices

Recent studies emphasize the need for evaluation practices that recognize diverse forms of scholarly contributions. Research by McGee et al. [136, 137] and other scholars underscore that traditional evaluation methods often fail to capture nontraditional teaching, mentoring, and community engagement activities faculty members of color typically engage in as a form of service [41, 81]. These additional service and mentoring responsibilities, which often go unrecognized in tenure and promotion decisions, are crucial for broadening participation in STEM and creating inclusive learning environments for all students and, in particular, underrepresented students.

Similarly other scholars [28, 41, 43, 45, 59, 138] contend that incorporating qualitative measures—such as narrative assessments, peer mentoring feedback, and evidence of community engagement—can provide a more accurate picture of faculty contributions and reduce the additional burdens placed on marginalized scholars. Without systemic changes in evaluation and promotion practices, the already low representation of marginalized faculty in STEM will persist. Research indicates that underrepresented minority (URM) faculty make up only 8.9% of STEM academic faculty, with even lower representation at senior ranks—only 3.9% of biology and chemistry faculty at the top 40 U.S. universities are from URM backgrounds [8]. The lack of equitable advancement opportunities contributes to the continued exclusion of diverse perspectives in STEM education and research.

The underrepresentation of marginalized faculty in STEM disciplines directly impacts STEM education in several ways:

1. *Representation and mentorship*: Diverse faculty serve as role models and mentors for all students, and in particular underrepresented students, supporting their retention and success in STEM fields. Research indicates that the presence of faculty of color increases the likelihood of students from similar backgrounds persisting in STEM programs [139]. The absence of these faculty members contributes to feelings of isolation among underrepresented students, which can negatively affect their academic trajectories.

2. *Curriculum and pedagogical innovation*: Faculty from diverse backgrounds bring perspectives that enhance STEM curricula, incorporating interdisciplinary approaches, culturally responsive teaching strategies, and real-world applications that resonate with a broader range of students [140]. Traditional evaluation criteria, which prioritize grant funding and publication volume over innovative pedagogical contributions, often devalue these efforts.

3. *Expanding research agendas*: Faculty diversity leads to a broader range of research questions and methodologies in STEM fields. Studies have found that underrepresented faculty are more likely to pursue research that addresses social and community-based issues in STEM, leading to innovations that have a direct impact on marginalized populations [141]. However, these contributions are often undervalued in promotion and tenure evaluations, limiting their influence within STEM academia.

4. *Institutional climate and equity*: Equitable evaluation practices contribute to a more inclusive institutional climate, which is critical for attracting and retaining both faculty and students from underrepresented backgrounds. Studies have shown that faculty of color frequently experience additional burdens related to diversity service work, mentoring, and advocacy, which are essential for institutional transformation but are not adequately rewarded in traditional promotion structures [142].

Transparent and inclusive tenure and promotion criteria are critical to addressing these disparities. By recognizing a broader range of contributions—including mentoring, community engagement, and teaching innovations—STEM departments can cultivate environments that support both faculty and student success. Reforming evaluation practices is not only an issue of faculty equity but also a necessary step in strengthening STEM education to better serve an increasingly diverse student population.

6.3 Fostering an inclusive culture: DEI initiatives and accountability

Beyond refining evaluation practices, institutions must proactively implement comprehensive diversity, equity, and inclusion (DEI) initiatives. Regular anti-bias training [25, 27] and the creation of structured support networks are essential for challenging systemic inequities. As Bercovici [143] and Hagner and Cooney [109] note, transparent communication—through centralized documentation of policies and clear guidelines—is crucial for reducing uncertainty and easing the burden on underrepresented faculty. By establishing accountability mechanisms and periodic assessments, universities can ensure that all faculty—especially those from neurodivergent and minoritized backgrounds—are supported and that their contributions are recognized. These reforms ultimately create an academic environment where digital learning and training tools and innovative practices can thrive in tandem with a fair and inclusive institutional culture.

7. Bridging the future: Recommendations for practice

To transform STEM higher education into truly inclusive and accessible environments, both technological innovation and institutional reform must work in tandem. Digital educational tools, when designed with universal design for learning (UDL) principles and an intersectional lens, offer promising opportunities to personalize instruction and create safe spaces for diverse learners. At the same time, comprehensive institutional policy changes are needed to dismantle entrenched biases and support faculty and students from underrepresented groups. The following recommendations are offered for practice:

7.1 Transparent communication and policy overhauls

Institutions should begin by centralizing and clarifying critical information related to academic expectations, promotion criteria, and evaluation processes. Standardized, easily accessible documentation can reduce ambiguity and lower the cognitive load on marginalized faculty and students [109, 123]. For example, clear guidelines about tenure and promotion processes have been shown to help counteract the “hidden curriculum” that perpetuates inequity [144, 145].

Research indicates that clear guidelines about tenure and promotion processes help counteract the "hidden curriculum" that perpetuates inequity. A study on pre-tenure faculty experiences found that unclear evaluation criteria contribute to uncertainty and stress, particularly among minoritized faculty members [144–146]. When institutions fail to make tenure and promotion expectations explicit, faculty from underrepresented backgrounds are often left navigating informal networks for critical information, further exacerbating inequities [147].

Moreover, ambiguous policies have been documented to contribute to role strain among neurodivergent and minoritized faculty. Universities often lack flexibility in adapting policies to accommodate neurodivergent faculty, leading to challenges in workload management, professional advancement, and workplace accessibility [28, 29, 45, 108, 148]. The absence of clear communication and policy accommodations can disproportionately increase the mental and emotional burden on faculty who already experience systemic barriers in academia.

In the context of STEM education, transparent communication also directly impacts student success. Research suggests that transparent teaching practices—where expectations, grading policies, and academic support structures are explicitly stated—enhance learning outcomes and retention, particularly for first-generation and underrepresented students [149]. The use of transparent communication strategies in STEM classrooms has been linked to greater student engagement, improved performance, and a reduction in achievement gaps for historically marginalized populations [150].

By implementing transparent, equitable evaluation practices, institutions can create environments that support the success and well-being of both faculty and students, thereby advancing diversity and excellence in STEM fields. Ensuring clarity in academic expectations is not merely an administrative necessity but a critical intervention for fostering an inclusive STEM educational landscape.

7.2 Designing user-centered learning tools for diverse learners

Digital tools, such as serious educational games and virtual laboratories, can provide personalized learning environments that allow students to engage at their own pace. By applying UDL principles, these tools can be designed to accommodate various learning styles and cognitive profiles, thereby creating "judgment-free" spaces for neurodivergent learners. For instance, virtual environments can offer real-time feedback and adaptive pathways that enable students to delve deeply into areas of strength while receiving supportive guidance on challenges. Such environments may be especially beneficial for learners with ADHD, who often ask many questions and benefit from non-judgmental, interactive feedback [84, 90, 91, 151]. In this way, personalized digital tools not only enhance engagement with complex STEM concepts but also foster the development of critical skills for real-world problem-solving.

7.3 Supporting neurodiversity and intersectional identities in STEM

In addition to technological innovations, institutions must implement targeted strategies to support neurodivergent faculty and students—particularly those who also face racial and gender biases. Ongoing anti-bias training, structured mentoring programs, and the creation of affinity networks can help build a supportive academic ecosystem [40, 128]. Furthermore, new assessment instruments—such as the Student Perceived Value of an Engineering Laboratory (SPVEL) validated assessment instrument [90, 91, 95]—can be used to evaluate the effectiveness of digital tools in reducing cognitive load and role strain. By regularly monitoring and adjusting both digital interventions and institutional policies, universities can ensure that all community members have the opportunity to contribute fully and authentically to the advancement of STEM fields.

8. Conclusion and global implications

This chapter has explored the multifaceted challenges of access and inclusion in STEM higher education by examining persistent systemic barriers, the evolving role of digital educational tools, and the pressing need for institutional reform. Drawing on empirical findings, and numerous other scholars, this work demonstrates that bridging access gaps in STEM requires an integrated approach—one that combines innovative digital interventions with transparent, equitable policies and supportive cultural practices.

8.1 Synthesis of key insights

STEM fields continue to grapple with longstanding inequities that limit the success of underrepresented groups. As Aguirre [6] and Ireland et al. [21] have noted, traditional institutional practices and biased educational cultures lead to persistent disparities in representation and access for women, African American/Black, Latiné, and Indigenous students. More recently, research has illuminated the "invisible" challenges faced by neurodivergent individuals—those with autism, ADHD, dyslexia, and related differences—which further compound marginalization [25, 27]. Previous work [28, 29, 73] has shown that when intersecting identities, such as race, gender, and neurodivergence, are considered together, the cumulative effects of systemic biases become even more pronounced.

In parallel, the rapid evolution of digital educational tools—including serious games and virtual laboratories—offers promising opportunities for personalized learning. By leveraging Universal Design for Learning (UDL) principles, these digital tools can provide real-time feedback, adaptive learning pathways, and judgment-free environments that help reduce cognitive and emotional loads [102]. Such environments are especially beneficial for neurodivergent learners, who may otherwise face additional challenges in traditional, neurotypical classroom settings.

Finally, the chapter underscores that meaningful change in STEM access requires not only technological innovation but also comprehensive institutional reform. Transparent communication, equitable evaluation practices, and robust diversity, equity, and inclusion (DEI) initiatives are critical for dismantling the "hidden curriculum" that perpetuates exclusion [107, 124, 152]. Together, these insights point to a dual strategy for transforming STEM education: one that marries user-centered digital innovation with systemic policy and cultural changes. Together, these insights point to a dual strategy for transforming STEM education: one that marries user-centered digital innovation with systemic policy and cultural changes, aligning with *SDG 4's* mission to ensure inclusive and equitable quality education and *SDG 10's* call to dismantle structural barriers that perpetuate inequality in higher education. By advancing both technological accessibility and institutional equity, STEM education can become a more just and inclusive space, fostering greater participation and success for historically underrepresented and neurodivergent learners.

8.2 Future research directions and call to action

While the integrated model presented here shows significant promise, several areas warrant further exploration. First, longitudinal studies are needed to assess the sustained impact of personalized digital tools on academic outcomes and career trajectories across diverse populations. Future research should employ mixed-methods approaches to capture both quantitative performance metrics (e.g., using validated instruments such as the SPVEL tool [90, 91, 95]; and the nuanced lived experiences revealed through auto/ethnographic inquiry.

Second, there is a critical need to examine the direct effects of institutional reforms—such as transparent promotion processes, standardized evaluation criteria, and ongoing anti-bias training—on the retention and success of underrepresented groups in STEM. Investigating how these structural changes interact with digital interventions can further illuminate pathways to reduce role strain and cognitive load among both students and faculty [108, 153].

I call on both researchers and academic administrators to embrace a holistic model of inclusion that combines user-centered digital learning with systemic institutional change. Such a model requires the design of learning environments that are accessible, adaptive, and reflective of diverse cultural and cognitive profiles. This is not simply a technological challenge but a call for comprehensive change in the values and practices that shape STEM education globally.

8.3 Final reflections on global implications

In a global context, the insights presented in this chapter have far-reaching implications. Institutions around the world face similar challenges of inequity, and the integration of personalized digital tools offers a way to bridge geographical and socio-economic divides. Virtual laboratories and game-based learning environments can democratize access to advanced STEM experiences, enabling students from under-resourced regions to engage with complex experimental practices in safe, controlled settings [116, 117]. These digital innovations support SDG 4's commitment to inclusive and equitable education by fostering problem-solving skills, creativity, and computational thinking, which are essential for success in the evolving global economy. Game-based learning environments and interactive simulations allow students to experiment, iterate, and apply STEM concepts in real-world problem-solving scenarios, cultivating both technical expertise and critical thinking abilities. These tools also align with SDG 10's mission to reduce inequalities by providing accessible, adaptive, and culturally responsive STEM education, ensuring that learners—regardless of their location, socio-economic status, or neurocognitive profile—can develop the skills needed to contribute to scientific and technological advancements on a global scale.

Moreover, the global conversation around diversity, equity, and inclusion is evolving. As nations strive to develop a more innovative and inclusive STEM workforce, the dual approach of combining technological innovation with institutional reform becomes paramount. By fostering environments that are both technologically advanced and culturally inclusive, we can empower every learner and educator to reach their full potential—regardless of their background. This chapter, therefore, serves not only as a reflection on current challenges but also as a roadmap for the future of STEM education—one where digital and institutional pathways converge to create a truly global, accessible, and equitable academic ecosystem.

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This book offers a critical perspective on key aspects of STEM education worldwide. Some empirical evidence is provided on best practices, encouraging the advancement of STEM education by showcasing various use cases. The book's primary purpose is to provide insights and inspiration for educators, policymakers, and anyone interested in the future of education.

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