education sciences

Integrated STEM and STEM Partnerships

Teaching and Learning

Edited by
Andrea C. Burrows and Mike Borowczak

Printed Edition of the Special Issue Published in *Education Sciences*

www.mdpi.com/journal/education

MDPI

Integrated STEM and STEM Partnerships: Teaching and Learning

Integrated STEM and STEM Partnerships: Teaching and Learning

Editors

Andrea C. Burrows
Mike Borowczak

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade • Manchester • Tokyo • Cluj • Tianjin

Editors
Andrea C. Burrows
University of Wyoming
USA

Mike Borowczak
University of Wyoming
USA

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Education Sciences* (ISSN 2227-7102) (available at: https://www.mdpi.com/journal/education/special_issues/stems_education).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-5649-9 (Hbk)
ISBN 978-3-0365-5650-5 (PDF)

Contents

About the Editors

Andrea C. Burrows

Andrea C. Burrows, Ed.D., is a Science Education Professor and the Director of the School of Teacher Education at the University of Central Florida (UCF). Previously, she served as the Professor and Associate Dean for Undergraduate Programs in the College of Education at the University of Wyoming. She earned an Ed.D. from the University of Cincinnati. She is the Association for Science Teacher Education's (ASTE) President for 2023–2024; Division chair for the Pre-College Engineering Education Division (PCEE) at the American Society for Engineering Education (ASEE); won the ASTE Award 1 (2021 Outstanding Science Teacher Educator of the Year); publishes regularly; received 10+ million in grant funding; is active in multiple organizations (e.g., ASTE and SITE); and is active with journal editorial boards (e.g., JSTE and CITE-Science). Her research interests include the science of teaching and learning, integrated STEM, partnerships, and K-12 pre-service/in-service teacher learning.

Mike Borowczak

Mike Borowczak, Ph.D, is currently an Associate Professor that holds the Templeton Endowed Professorship of Electrical Engineering and Computer Science at the University of Wyoming. He also serves as the Director of the Cybersecurity Education and Research (CEDAR) Center and Lab and is the Co-Director of the Advanced Blockchain Research and Development Lab. He is a former hardware security architect and data scientist, having worked in both the semiconductor industry as well as several since-acquired startups. His research interests include secure distributed systems, security and resilience of autonomous systems, continuous and adaptive authentication, cyber-physical systems and applications, and hardware-level security for lightweight agents. Working with his students, he has published many journal and conference publications. He is a senior member of the IEEE, ACM, and IET. His research has been funded (USD 10M since 2018) by federal, national, state, and industrial entities, including the NSF, NSA, Idaho National Laboratories, State of Wyoming, IOG, and Kraken.

Preface to "Integrated STEM and STEM Partnerships: Teaching and Learning"

This Special Issue focuses on Integrated STEM and STEM partnerships as they relate to teaching and learning. The articles included have been grouped into three main categories (i.e., partnerships (first four articles), real-world issues (middle three articles), and curriculum (last three articles)) and highlight areas of interdisciplinary science, technology, engineering, and mathematics. Furthermore, teamwork is explored in STEM spaces. The guest editors encourage the reader to utilize the expertise and ideas presented for their own research contexts. The guest editors would also like to acknowledge and thank the 36 authors who contributed to this Special Issue (ordered alphabetically by last name):

Zubair Ahmad, Qatar University, Qatar;
Noora Al-Thani, Qatar University, Qatar;
Mohammad Ammar, Qatar University, Qatar;
Orlando Ayala, Old Dominion University, USA;
Ali Bicer, University of Wyoming, USA;
Andrea C. Burrows Borowczak, University of Central Florida, USA;
Mike Borowczak, University of Wyoming, USA;
Malcolm Butler, University of North Carolina, USA;
Claudia Canali, University of Modena and Reggio Emilia, Italy;
Antonella Carbonaro, University of Bologna, Italy;
Michele Colajanni, University of Bologna, Italy;
Emily Anna Dare, Florida International University, USA;
Lisa Dieker, University of Central Florida, USA;
Francesco Faenza, University of Modena and Reggio Emilia, Italy;
Su Gao, University of Central Florida, USA;
Lorenzo Gonzales, Los Alamos National Laboratory, USA;
Kristie S. Gutierrez, Old Dominion University, USA;
Benny Mart Hiwatig, University of Minnesota, USA;
Krishnanand Kaipa, Old Dominion University, USA;
Khomson Keratithamkul, University of Minnesota, USA;
Jennifer J. Kidd, Old Dominion University, USA;
Trina J. Kilty, University of Wyoming, USA;
Richard Kitchen, University of Wyoming, USA;
Yew-Jin Lee, Nanyang Technological University, Singapore;
Min Jung Lee, Old Dominion University, USA;
Feng Li, Florida International University, USA;
Monica Martinez-Archuleta, Los Alamos National Laboratory, USA;
Thomas Meagher, University of Minnesota, USA;
Bekir Mugayitoglu, Georgia College and State University; USA;
Enrique Ortiz, University of Central Florida, USA;
Pilar Pazos, Old Dominion University, USA;
Stacie I. Ringleb, Old Dominion University, USA;
Elizabeth A. Ring-Whalen, St. Catherine University, USA;

Gillian H. Roehrig, University of Minnesota, USA;
Timothy Ter Ming Tan, Nanyang Technological University, Singapore;
Jeanna R. Wieselmann, Southern Methodist University, USA.

Andrea C. Burrows and Mike Borowczak
Editors

education sciences

MDPI

Article

Reflecting upon 30 Years of STEM Partnerships between Industry, University, and Public Schools: Past Lessons, Current Successes, and Future Dreams

Lisa A. Dieker *, Malcolm B. Butler, Enrique Ortiz and Su Gao

School of Teacher Edcuation, University of Central Florida, Orlando, FL 32816, USA;
malcolm.butler@ucf.edu (M.B.B.); enrique.ortiz@ucf.edu (E.O.); su.gao@ucf.edu (S.G.)
* Correspondence: lisa.dieker@ucf.edu

Abstract: The importance of partnerships is critical in educational arenas, but information on how partnerships form with the involvement of corporations, districts, and universities working in harmony is limited in the current literature. The teacher preparation program described in this paper is a "built-to-last" partnership model with over 650 teachers prepared to be teacher-leaders in science, technology, engineering, and mathematics (STEM) education. The authors provide a history of the program's development, the sustainability of the program over time, the content of the various components of the partnership, and the evolution of the program, including its current status.

Keywords: STEM; teacher preparation; partnership; diverse learners

Citation: Dieker, L.A.; Butler, M.B.; Ortiz, E.; Gao, S. Reflecting upon 30 Years of STEM Partnerships between Industry, University, and Public Schools: Past Lessons, Current Successes, and Future Dreams. *Educ. Sci.* **2021**, *11*, 760. https://doi.org/10.3390/educsci11120760

Academic Editors: Andrea Burrows and Mike Borowczak

Received: 17 September 2021
Accepted: 14 November 2021
Published: 24 November 2021

1. The Literature Framing the Partnership

Finding innovative ways to keep teachers in the field while promoting the overall impact on student learning is the theme of this article. The authors highlight a current partnership between a university, a large corporation, and surrounding school districts. The focus of this partnership emerged and continues today to address key variables noted in the literature as to why teachers leave the field: (1) lack of preparation for the content (e.g., mathematics and science), (2) lack of preparation for pedagogical practices to ensure student engagement and learning outcomes [1], and (3) high rates of stress and burnout [2]. Research on teacher preparation indicates a need to support teachers in both learning the content and creating a classroom culture that engages students [3,4]. The stress on teachers has increased over the years, especially in STEM content areas, as they strive to meet the needs of a more diverse set of learners who are expected to meet and even exceed local, state, and national standards [5–7].

Despite high expectations for outcomes and rigorous learning standards, Banilower et al. suggest a flat trajectory in adjusting to major reform efforts in teaching practices aligned with these expectations [8]. With the stakes high for learning outcomes for both teachers and students alike in STEM areas, one approach to addressing this increasing stress began in 1992 through a partnership formed between a university and an industry partner. This partnership impacted and will continue to forever influence teachers with regard to leadership, retention, and increasing student learning outcomes. The program also focuses on advancing teacher knowledge in terms of both content and pedagogical practices. The authors of this article provide the field with a summary of this "built-to-last" [9] mindset underlying this teacher preparation program built through sustained partnerships. They provide the literature grounding the principles of the program, the domains of the content of the program, and the demographic and evaluation data documenting the success of the program. In addition, they provide a history of the program's development, the sustainability of the academy over time, the intricacies of the partnership, and the progress of the program in serving a range of teachers in STEM areas.

The University of Central Florida (UCF) and Lockheed Martin Mathematics and Science Academy (LMA) began in 1992 with one program focused on retooling and preparing K–8 teacher-leaders in mathematics and science. Today, the LMA program has expanded to three different venues, with each built upon increasing teachers' skills in three domains: (1) mathematics instruction, (2) science instruction, and (3) teacher leadership in meeting the needs of diverse learners. The program faculty members have responded to the shift in standards as well as the stress of being a teacher by creating a cohort program. The local school districts view the program as one of many strategies to prepare, retain, and further promote teacher leadership. The work of the LMA is aligned with attracting, retaining, and recruiting the best and brightest to teaching, with a specific focus on retooling and enhancing skills in STEM-related content.

The LMA team responds to this need for retooling as one of many ways to address the exorbitant cost of teacher turnover, being at least $2.2 billion per year [10]. As Carver-Thomas and Darling-Hammond emphasized, the creation of the annual demand for teachers comes not from a shortage of preparing enough but from the almost immediate exiting of those prepared [11]. An annual poll by Phi Delta Kappa further showed over half of teachers wanting to leave the field, with 19% of those citing stress, pressure, or burnout as the primary reason [12]. Elementary teachers specifically struggle with being prepared and feeling they are adequate at teaching STEM content [13]. In contrast to these findings, the typical LMA scholar remains in teaching for eight or more years, with over 60% who are eligible to retire staying throughout their career [14].

The LMA team is grounded in closing gaps of confidence in STEM content or those who might have content expertise but fail to know how to address a wide range of learners' needs in their areas of expertise [15–17]. The LMA faculty also ground their thinking in an important element of successful inquiry in mathematics or science, ensuring student engagement in discourse [18]. The academy faculty embrace the concept of discourse, with their foundation in the social and cultural views of the ways people linguistically interact. Gee defines discourse as the combination of the conversation paired with the interactions or ways of acting that emerge from unique conversations [19]. Gee's definition insists discourse orchestrates change and understanding from an exchange of ideas. A teacher's ability to allow for the process of inquiry along with discourse increases a student's ability to engage with the content and retain information [20]. The domains of instruction within the academy are framed in the power of discourse led by teachers who help to elevate students' voices, understandings, and learning outcomes in the critical areas of STEM. Many of the academy scholars are working with diverse learners, with 125 teachers currently in the K–8 Mathematics and Science Education M.Ed. program and the Transition to Mathematics and Science Teaching (TMAST) being employed in Title I schools.

2. Methods and Materials: The Solution to Today's Issues Began 30 Years Ago

The formation of this academy is one that is unique and somewhat of an anomaly in the partnership with UCF, the Lockheed Martin Corporation (LMCO), and local school districts sustaining this program over the past 30 years [21]. The authors provide a history of the development of the program from both program archival data and ongoing annual external evaluations to help others understand the power of true industry, university, and district partnerships [21]. The academy team notes that these relationships take time to both develop and sustain while maintaining a positive reputation for all involved. Most importantly, the academy, its faculty members, and its teachers have retooled themselves as standards changed, the needs of the community changed, and even priorities changed (e.g., teacher shortages). For example, the 2008 economic recession hit Florida very hard, being ranked as the 48th state with the greatest loss in revenue [14], and the academy team pivoted to address layoffs in STEM areas to fill gaps in shortages of teachers. During the recent COVID-19 pandemic, the team shifted again to think about teacher leadership in STEM content through virtual and socially distanced settings. One of the lessons learned by the academy leadership team was that with a strong foundation, shifts can happen with a program built upon a shared community of problems and with investments by all partners involved (i.e., industry, districts, and the university).

The directors of the academy documented the creation and evolution of the academy through historical records at UCF. The academy formed in 1992 when LMCO, who built two major facilities in the Central Florida area, realized the pending shortages they would encounter in engineers in Central Florida and nationwide. The LMCO, in response to a need for more engineers, offered several large grants to increase the supply chain of students prepared with advanced STEM content skills in the early elementary grades to enter advanced STEM content aligned with engineering degrees. Therefore, LMCO provided substantial funding to key universities to impact the trajectory of students in STEM fields. The University of Central Florida applied for and was awarded a grant for USD one million to support teacher development in Central Florida STEM education. The UCF leadership in 1992 had a vision for this USD one million grant and asked if funds from the LMCO could be endowed instead of provided as a grant. The UCF leadership team informed the LMCO leaders that if the gift was over USD one million, the state would provide a 50% match. Therefore, the final check, given in 1992 to UCF, was for USD 1,000,001, with a USD 500,000 match from the state collectively going into an endowment. This idea of a corporation providing funding to teacher education through an endowment was a novel, creative, and impactful concept that today provides never-ending funds from the interest of the initial gift. The process to endow these funds instead of receiving a grant and garnering a match from the state took several rounds of negotiations between legal teams. The outcome in 1992 was, and today still is, a sustained, innovative, and most importantly impactful program to "forever" support K–8 teachers as leaders in STEM and the students they teach in the Central Florida community.

This university, corporate, and school district partnership has reaped additional benefits beyond this sustained program. Originally, the program, endowed in 1992, was set to begin in 1996, when the interest from the USD 1,501,000 reached a level to support the first cohort of teachers. However, the UCF leadership team leveraged this partnership investment to approach the National Science Foundation (NSF) for a grant to fund cohorts of teachers until the endowment matured. The funds garnered from the NSF afforded the academy the opportunity to support teachers immediately. Thus, from 1992 to 1996, over 60 scholars graduated while the endowment grew. This initial gift, along with funds from the NSF, jump-started the program while allowing this foundational funding to maintain a program 30 years later.

3. Reflections on the Evolution of the Partnership

3.1. University of Central Florida and Lockheed Martin Academy Programs

The University of Central Florida was founded in 1963, with its first class graduating in 1969. In juxtaposition, today, the university is eligible for Title II funding as a Hispanic-serving institution (over 27% of students are of Hispanic culture) and has over 70,000 students enrolled [22]. The university, even in 1992, was well-positioned to support the mission of the LMA with an increasingly large teacher preparation program. The LMA program is an education, industry, and community partnership aimed at improving STEM education in Central Florida. This unique partnership serves as a model for the educational reforms proposed by both national and state agencies by providing schools in Central Florida with teacher-leaders who initiate, implement, and sustain STEM reform efforts. The profile for the funding and support of LMA includes the following:

(a) The LMCO provides the stimulus for the development of the LMA concept through an endowment to ensure the longevity of the program;
(b) The Board of Regents of the State University System (SUS) of Florida provides matching funds to attain the LMA's goals;
(c) The University of Central Florida commits to support the development of the academy through new faculty lines, priority course scheduling, and faculty support.

Although the initial gift to the academy was to fill the gap for K–8 teachers in STEM areas, since 2004, the LMCO granted two additional gifts to the UCF LMA to create additional programs to impact teachers in Central Florida: the Transition to Mathematics and Science Teaching (TMAST) program and the K–8 Teacher Enhancement program. Components of each of the three programs that grew from this initial partnership are provided.

3.2. K–8 Program

The mission of the K–8 Mathematics and Science Education M.Ed. degree is to improve the quality of mathematics and science teaching in Central Florida through (1) strengthening the quality of teaching and learning in STEM, (2) creating a network of school-based leadership in STEM, and (3) increasing the number of students choosing to enroll in STEM courses aligned with careers in STEM-related fields.

In this context, the teachers in the K–8 program participate in six semesters of coursework, with six credits each semester (Table 1). The teachers enter the program in a cohort and complete the courses together while teaching full time in their respective districts. All teachers recruited into the program must have three or more years of teaching experience, have an undergraduate GPA of over 3.0, complete a summary of their teacher leadership experiences, and provide a required letter from their current administrator. The teachers complete a series of courses found in Table 1 reflecting the program foci of (1) mathematics, (2) science, and (3) leadership for diverse learners.

Table 1. Components of the UCF and Lockheed Marting program and course sequence (K-8 Graduate Program).

Semester	Courses
	Space and Physical Science for Educators Problem Solving and Critical Thinking Skills
2	Data-Driven Decision Making for Instruction Reforming Curriculum in Mathematics and Science Education
3	Seminar in Teaching Mathematics Seminar in Critical Issues in Special Education
4	Environmental Education for Educators Leadership Development for Mathematics and Science Teachers
5	Current Methods in Elementary School Mathematics Research in Mathematics and Science Education
6	Teaching Mathematics and Science Using Reform-Based Practices Quality Teaching Practices (Action Research Capstone Course)

Mathematics Components (Table 1). When conceptualized, the K–8 program includes a core component in mathematics, and this component continues to evolve today. This aspect of the program includes three integrated courses with an emphasis on scholars' pedagogical content knowledge and utilization of project-based learning activities (PBL). One of the courses is a seminar in teaching mathematics, which presents the development of historical and current issues, forces, and the impact of the teacher on student learning through advanced instructional techniques (e.g., cooperative learning, discourse, and noticing). The second course is about current methods in elementary school mathematics. This course includes strategies of instruction, of computation and concepts of numbers, geometry, measurement, algebra, and professional standards for teaching mathematics. The third course is about problem-solving and critical thinking skills. The faculty member in this course emphasizes the development of procedures and practices to implement critical thinking skills and problem-solving techniques for learning.

These courses have two common threads: pedagogical content knowledge and PBL. The emphasis on scholars' development of pedagogical content knowledge goes beyond mathematics knowledge. The teachers' deep understanding of mathematical content is necessary but not sufficient to teach mathematics effectively. Shulman stated that pedagogical content knowledge is used by effective teachers when they possess an in-depth knowledge of how to effectively represent the subject matter to learners [23,24]. Additionally, pedagogical content knowledge should include teachers' knowledge of learners' needs, learning styles, environments, goals, purposes, and values. The LMA team encourages scholars to develop the ability to transform mathematics content into pedagogically powerful learning activities for the students' diverse learning abilities and backgrounds in their classrooms [23].

The core use of PBL allows teachers to create and implement learning activities that support their development of pedagogical content knowledge. The PBL method allows students to learn by actively engaging in real-world and personally meaningful projects. The scholars learn about PBL by experiencing this type of approach throughout their courses. The scholars in evaluations of the program note the power of learning by example and reflecting upon the deep learning they experience using this approach.

Science Components (Table 1). The designers of the K–8 program also realized the need to have a strong science component in the program. The result was two content-focused course offerings aligned with the science taught in elementary and middle schools. Both courses provide opportunities for teachers to view science through the lens of a learner, instructor, and leader. The two courses take advantage of the plethora of informal science-based settings at the university and in the central Florida region. Additionally, the two courses are taken during different semesters so the scholars can have time to process and refine their instructional skills around the teaching of science.

The first course emphasizes environmental science. During the weeks of this course, the scholars are engaged in numerous activities requiring them to re-visit their current instruction related to nature and the environment. Collectively and individually, scholars are challenged to consider how they might use learners' local communities in the science classroom. Field trips to local places help scholars to "connect the dots". Several action research projects have this course as their genesis.

The second science course focuses on physical and space science. Similar to the environmental science course, scholars experience science in ways that their students might. Notably, these science topics are taught with the understanding they could be difficult topics for the scholars [25]. For example, the scholars visit the Kennedy Space Center and its education center, which is typically the highlight of this course. Scholars come away from this course with a deeper understanding and appreciation for physical science and space science, as well as how to help young learners appreciate and understand these science content areas.

Teacher Leadership and Diverse Learners (Table 1). The third set of courses prepares scholars to serve as leaders in meeting the needs of all learners, with a particular emphasis on those underrepresented in STEM. This component includes a sequence of courses on leadership combined with specific courses on leadership in mathematics and science inquiry. This component of the program also includes a course on current issues and trends in special education, inclusive of topics of diversity, universal design for learning, and creating inclusive leadership within the district. This portion of the program concludes with a two-course sequence focused on teachers as researchers to lead change. These courses require the participants to conduct an in-depth literature review aligned with their desired action research study in their final semester.

The K–8 program is evaluated by an external evaluator every 2 years. The program consistently receives outstanding reviews by the scholars. Any area of concern that arises is addressed by the leadership team. The team conducts an extensive review bi-annually, but each semester they review course evaluations to update content or seek more effective instructors, if necessary. Additionally, course instructors listen to scholars' feedback throughout the program to ensure the best outcome for the teachers in meeting the needs of their learners in STEM areas. Provided in Table 2 are a few select comments from scholars about the program [21].

Table 2. Comments from UCF and Lockheed Martin program scholars.

Comments about the Most Valuable Outcome of the Program for Learning [21]
"Being able to apply the learned contents into my classroom, regardless of their abilities."
"The new learning strategies I can now apply to my teaching."
"Focus on science and math."
"Cohort instruction, reasonable schedule with teaching."
"The professors' active knowledge about current classroom situations and state standards."
"The program has given me the confidence to be a leader in mathematics, and I feel more confident teaching science when I didn't before this program."
"I loved the professors' passion & investment in each of us, along with their inspirational knowledge base. I liked that everything was immediately applicable to my classroom as well."
"I liked learning new strategies and the way we should develop the class."
"I liked meeting with and learning from knowledgeable professors, as well as working with distinguished colleagues throughout OCPS."

Action Research Project. The culminating aspect of the program is an action research project. Scholars begin to conceptualize this project upon entering the program and build upon a topic of choice throughout the six semesters. The action research is framed in a variety of methodologies inclusive of gathering data in a perceived area of current weakness in their classrooms and schools in STEM. Unlike more formal research master's theses, action research is typically within the school or classroom, but in the LMA, these practices are specifically targeted in areas of teacher leadership for diverse learners in STEM content. The action research process involves less-formal, theory-driven methodologies. The goal of the LMA faculty members is to help teacher-leaders in the program address practical problems in their specific school or classroom [26]. The general goal of the culminating activity of the action research project is to find a practical approach to improving learning outcomes in STEM.

The process LMA teacher scholars engage in for their action research projects within the academy follows predefined steps built upon the work of numerous researchers in the field [26–31]. These steps begin in their fifth semester and culminated with a presentation of their work in the sixth and final semester. The steps used to guide the action research studies are (1) identify the problem, (2) develop a data-driven plan to address a problem focused on impacting student learning in STEM, (3) implement the plan, (4) collect data on the identified problem aligned with STEM learning, (5) organize, analyze, and interpret the collected data on STEM learning, (6) evaluate the results of the action taken and make further changes beyond the findings to ensure a mindset of constant change and future leadership in impacting student learning outcomes, and (7) conclude the project by determining the identified but still unresolved problems and future plans. The outcome of this systematics process is to ensure these teachers are prepared as ongoing teacher-leaders to impact the outcomes of diverse learners in STEM content.

Since the fall semester of 2019, LMA scholars have completed action research projects as part of their capstone project requirement of the program. Prior to 2019, scholars completed a more traditional master's thesis, which is still an option today. For the action research project, scholars can individually or in small collaborative groups of 3–4 scholars complete their projects. Since 2019, a total of 106 scholars have completed action research projects analyzing issues or challenges in their own classroom teaching practices in STEM areas. An action research project includes elaboration of research questions, selection and application of research methodologies, a literature review, implementation of a research plan, data collection, and analysis. As part of the capstone course, the culminating activities consist of a final report and poster presentation. The scholars are also supported in submitting their manuscripts to peer-reviewed journals. Faculty or LMA alumni collaborate as research advisors with the scholars in the development of the action research. A sample of past action research questions investigated include the following:

(1) If teachers are exposed to workshops involving questioning techniques to promote problem solving in the classroom, how will this approach impact their questioning skills when teaching students about solving systems of linear equation word problems?
(2) If students are exposed to problem-solving strategies, how will the approach impact the students' ability to solve systems of linear equation word problems?
(3) If I involve parents in guiding their children during STEM experiments at home, will the students demonstrate improvement in their understanding and self-efficacy of the engineering design process?
(4) If I involve parents in guiding their children during STEM experiments at home, will the parents demonstrate improvement in their perceptions of self-efficacy to help their children complete STEM experiments?
(5) How will implementing alternative ancient Egyptian computation algorithms using an ethnomathematics context impact fourth-grade marginalized students?
(6) If we use iReady mathematical games to help first- and fourth-grade students learn computation of whole numbers, then will students demonstrate improvement in solving the computation of whole number problems?
(7) If I implement interactive cross-curricular content using Nearpod (n.d.) during remote learning mathematics instruction, then will third-grade students demonstrate improvement in engagement with and understanding of fractions [32]?
(8) If I implement flipped-classroom intervention in a remote classroom environment, then will my AP Calculus students demonstrate improvement on their test scores and grades?
(9) How does explicit instruction in group collaborative skills affect fourth graders' ability to work as a team to create a final product?
(10) How will explicitly teaching collaborative techniques alter fourth graders' ability to work together in an engineering task?

This list is a small sample of the 106 ideas scholars have addressed through their action research projects. The LMA faculty members' primary goal in the action research projects is to encourage the teachers to continuously think about their ability to lead change using data-driven solutions to problems of practice.

3.3. TMAST Program

The second program that emerged from another generous gift from the LMCO partnership was the Transition to Mathematics and Science Teaching (TMAST) program. This program is a fast-track Master of Arts program for individuals with interest in becoming teachers as a second career choice who have STEM backgrounds. The LMA leadership team went to the LMCO leadership after the success of the K–8 program in 2004 and received another gift for USD 750,000. This gift was also endowed and received a match from the state Florida for USD 200,000 to address the critical shortages in Central Florida of STEM content teachers in grades 6–12. This program aligns with the emphasis of Johnson et al. in their Handbook of Research on STEM Education for the need to have teachers who know science content and pedagogical skills [16]. This fast but intense preparation of these career changers (who already received 16–32 credits in STEM content) addresses the critical teacher shortages while providing content, mentoring, coaching, funding, and support to decrease the USD 2.2 billion per year churn of novice teachers who enter the field [10,11].

The TMAST teachers in both the science and mathematics track have the same type of support during student teaching and on-the-job learning. As noted by Sutcher et al., keeping mathematics teachers in the classroom is a crisis in public education [33]. In their study, the District of Columbia and 42 states reported the challenges they had with mathematics teacher shortages, their plans to reduce pupil/teacher ratios, and how their intention to hire as many mathematics teachers as possible to serve those students was critical, much like what was observed in the Central Florida area in creating the TMAST program. Teacher workforce attrition accounts for the loss of thousands of teachers every year [34]. Interview results from four sites also supported the idea that providing well-tailored, continuous professional development could enhance teachers' efficacy, motivation, and retention and was a built-in component of the TMAST program [10]. As noted by Ingersoll and Smith, "beginning teachers who were provided with multiple supports, were less likely to move to other schools and less likely to leave the teaching occupation altogether after their first year" [10] (p. 28). The TMAST program is built on this evidence-based approach to attract career changers to the profession while providing support for retention.

Since 2003, over 100 teachers have completed the TMAST program. These candidates bring both strong content knowledge and professional experiences in the STEM areas to educational settings in grades 6–12. The TMAST program aligns well with the needs of the candidates by providing tracks in the areas of mathematics, biology, chemistry, and physics for middle or secondary school levels. A Noyce grant from the NSF initially supported students in the TMAST program. The grant was successful in recruiting mid-career professionals with mathematics or science backgrounds and helping them become effective mathematics or science middle or secondary school teachers. The Noyce grant also provided a recruitment tool of financial support aligned with the high-quality four-semester pedagogical preparation. The content of these four semesters includes instructional methods, learning theories, development of teaching goals, understanding high-need local educational agencies serving diverse student populations, educational measurement and assessment, and understanding of the educational contexts that impact young adolescent learners. The program also provides salaries and benefits as the TMAST scholars are given on-the-job internship placements once they have a provisional license. This on-the-job fast-track program has led to retention of the TMAST scholars in education. The Noyce grant provided USD 10,000 fellowships on top of the LMA endowment covering tuition, plus mentoring by LMA faculty to support them. Fifteen of the 20 Noyce TMAST graduates remain in teaching positions at low socioeconomic schools today. The design and partnership aspect of the program serves as a national model for other universities interested in implementing sustainable programs to help professionals from the STEM community transition and stay in the teaching profession.

Mathematics and Science Track TMAST. Since all the TMAST candidates have a bachelor's or higher degree in the content areas, the courses for the program focus more on the inquiry of teaching, learning theories, and instructional methods. For example, in the course entitled "Issues and Methods in Secondary School Science Education", TMAST teachers are provided a series of opportunities to learn the 5E learning instructional model [35] in designing a unit plan to promote students' deeper engagement in science and engineering practices [36], develop instructional objectives for each science lesson to include three components (i.e., performance, condition, and criterion), plan and conduct formative and summative assessment to ascertain students' science learning, and use differentiation methods to meet diverse students' needs. Furthermore, TMAST teachers are provided an on-the-job internship to make more connections between the courses and their practices in the classrooms. During this internship, UCF coordinators work closely with TMAST students to support their planning, enacting, interpreting, translating, and (re)enacting processes in authentic learning contexts. The internship supports TMAST teachers in constructing and understanding the substantive relationships between learners, learning, pedagogy, and learning outcomes. See Table 3 for the course sequence for the program.

Table 3. UCF and Lockheed Martin TMAST program's teaching course sequence. UCF and Lockheed Martin Transition to Mathematics and Science Teaching.

Semester	Credits	Courses
1 **Summer**	**9**	Teaching Middle School Science OR Teaching Middle School Mathematics Theory and Practice of Teaching ESOL Students in Schools Content-specific course in mathematics or science content
2 **Fall**	**9**	Literacy Strategies for Middle and Secondary Teaching Classroom Management for Mathematics and Science Teachers Internship
3 **Spring**	**9**	Reforming Curriculum in Mathematics and Science Education Principles of Learning and Introduction to Classroom Assessment Internship
4 **Summer**	**9**	Critical Analysis of Social, Ethical, Legal, and Safety Issues Related to Education Teaching Algebra in Secondary Schools OR Space Science for Educators OR Environmental Education for Educators Capstone Seminar in Secondary Education

3.4. Enhancement Grants

Based upon the ongoing success of the academy and the rising cost of tuition, the LMA leadership team approached the LMCO once again and received a third endowment gift in 2012 for USD 500,000 with match eligibility by the state which, to date, has not yet occurred. This gift request was funded for two purposes. The first purpose was to provide additional tuition support from the gift endowed in 1992 to address the rising cost of tuition. The second purpose was to provide past LMA participants who wanted to retool their skills in mathematics or science the chance to attend workshops, conduct innovative practices in their classrooms, attend and present at practitioner conferences, or purchase supplies for mathematics or science projects. A past LMA graduate can compete for a USD 1000 grant. Each application consists of a short essay that explains the purpose and significance of the potential project and a budget outlining how the funds will be spent. Priority is given to applicants with (1) the most time lapsed since graduating from the academy and (2) individuals whose current roles directly impact student learning in mathematics or science. A condition of receiving a grant is the expectation the recipient will share their learning with current LMA scholars. The Enhancement Scholarship provides a way to ensure life-long learning and leadership of the LMA scholars.

Samples of some of the projects funded at this time include the STEM Bowl Competition in robotics and coding, exploring various resources (e.g., unique joysticks and other evolving devices) to teach engineering design and computer programming, attending a National Science Teacher Association STEM Conference, increasing students' engagement using various web-based technology tools, and taking content courses at UCF to teach comprehensive science. These grants from the endowed gift allow LMA graduates to stay connected to UCF and empower these teacher-leaders with funds to retool their STEM skills throughout their careers.

4. Current Status of the Program and Partnership

Since the inception of the program and partnership in 1992, the LMA program has grown substantially. Recently, a newly cemented partnership for teacher retooling and retention was finalized with a local district. Since 1992, teachers attending the program have come from six districts surrounding UCF, all of whom have long-standing relationships with the university. As the incentive to receive a masters or to be nationally board-certified (which was at one time a component of the program) no longer received financial incentives from the state teacher to increase teacher pay, and UCF tuition costs rose simultaneously, the number of teachers entering the K–8 program decreased. The LMA faculty members realizing a need to pivot again to ensure the sustainability of the program looked once again at the power of partnerships. The academy partnering with a local district began to explore a pathway to grow the program while meeting the partnership goals and needs in staffing, supporting, and retaining teachers in Title I schools.

A culmination of these discussions resulted in an agreement for the district to match funding from the academy to fully fund the master's degrees of a cadre of 20 teachers in Title I schools. The district also offered a large stipend to teachers in these rich and diverse schools to ensure the students had the best of the best teachers. These schools received numerous applications, and the academy received a rich and diverse pool of outstanding teacher-leaders. This partnership between the district and the academy created the ideal scenario for a new venture. The academy faculty members immediately engaged their corporate partnership with the LMCO to help highlight the outstanding contributions of these teacher-leaders. The first group of teachers invited into this "elite" cohort were presented to the corporate sponsor and the local school board—who was supporting their funding—with each teacher receiving a lab coat (as seen in this article https://www.ucf.edu/pegasus/helping-public-school-teachers-earn-free-masters-degree/, accessed on 10 November 2021), highlighting their entrance as K–8 teachers into the STEM fields. This partnership not only increased the retention of these teachers in their positions, as they received 100% tuition support in return for staying a minimum of 3 years and a pay raise upon completing the master's degree, but most importantly, they felt empowered, appreciated, and entitled to lead. These teachers provided a new mindset in STEM education for the students they were teaching in Title I schools. In return, the university had a large and sustained cohort of teachers with rich experiences (average teaching experience of 7 years), and the diversity of the scholars exceeded the past percentages of diversity (46% reported being from diverse backgrounds) of the LMA program and the university, which is designated as a Hispanic-serving institution (meaning over 25% of UCF's students in undergraduate enrollment are Hispanic). Today, this partnership continues to fund a cohort annually with funds from the academy, the district, and Title I funding of up to 30 teachers annually. Prior to this new partnership, the interest from the endowment supported approximately 10 teachers per year, showing the power of this expanded partnership, which has tripled the impact in terms of the number of currently enrolled LMA scholars (30 per year).

5. Future Dreams and Reflections

The dreams of the LMA faculty members and their partnership districts are to create changes in student learning outcomes in STEM content. As noted by the U.S. Department of Labor (2017), the top 30 occupations to grow the fastest by 2026 are those in STEM fields [37]. This partnership between the LMCO, UCF, and local districts creates opportunities to prepare students in Central Florida for the needs of industry partners in STEM areas. Simultaneously, this newest partnership, working with over 150 teachers to this point in Title I schools, creates the potential for an increased trajectory for the diversity of individuals entering STEM fields. These LMA teacher-leaders in these Title I schools, through their coursework and action research, are agents of change.

This type of direct support to practicing teachers in both the K–8 and TMAST programs also aligns with current U.S. Department of Education initiatives outlined in their roadmap to provide support to teachers in Title I schools for recruitment and retention [38]. Currently, the TMAST scholars primarily work in Title I schools. The LMA faculty members dream of not only better prepared teachers in STEM, but that this program continues to address key variables concerning why teachers leave the field. Many of the teachers in the program stay through retirement. Many may move into district leadership roles of curriculum directors, administrators, or coaches, but the true dream of the program faculty members is that the individuals who graduate stay because, as seen in Table 3, they are better prepared to not leave due to (1) better preparation for the content (e.g., mathematics and science), (2) better preparation in pedagogical and content practices [1], and (3) better preparation to address the high rates of stress and burnout [2] due to the ongoing and sustained support of the academy.

The UCF academy faculty members applaud the vision of the LMCO to support universities in helping to prepare stronger teacher-leaders in STEM to deal with shortages in these content areas. The need for a strong STEM workforce is critical in Central Florida, with our increased industries in simulation, space exploration, entertainment, and technology, along with a great migration post-pandemic to this vibrant area of the state. The vision and support of the LMCO, combined with a university in its youth (compared with the ages of other institutions of higher education) and the perfect partnerships of local school district leaders created in 1992, remains vibrant today as a program to impact the children and teachers in Central Florida in STEM areas. Thirty years ago, little did anyone know the exponential, sustained, and eternal impact of this gift based on a "true" partnership model. The ultimate dream is to create additional sustained partnerships to serve the greater good of all of society, as that is truly the purpose of partnerships in education.

Author Contributions: Conceptualization, L.A.D.; validation, L.A.D., M.B.B. and E.O.; formal analysis, L.A.D.; resources, S.G. and E.O.; data curation, L.A.D.; writing—original draft preparation, L.A.D.; writing—review and editing, E.O.; supervision, M.B.B.; project administration, M.B.B., E.O. and S.G.; funding acquisition, L.A.D. and M.B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This program was funded by an endowment from the Lockheed Martin Corporation to the University of Central Florida, with matching funds from the State of Florida Board of Governors, Title 1 funds, and district partnership matching funds.

Institutional Review Board Statement: Ethical review and approval were received by the independent evaluator for the UCF Lockheed Martin Academy who obtained informed consent. The information beyond the evaluation did not involve human subjects.

Informed Consent Statement: Not applicable.

Data Availability Statement: Evaluation data for this program can be obtained Program Evaluation and Educational Research Group (PEER), A Service Center at the University of Central Florida via email to peer@ucf.edu.

Conflicts of Interest: No conflict of interest.

References

1. Ekstam, U.; Korhonen, J.; Linnanmäki, K.; Aunio, P. Special Education and Subject Teachers' Self-Perceived Readiness to Teach Mathematics to Low-performing Middle School Students. *J. Res. in Spec. Educ. Needs.* **2018**, *18*, 59–69. [CrossRef]
2. Rumschlag, K. Teacher Burnout: A Quantitative Analysis of Emotional Exhaustion, Personal Accomplishment, and Depersonalization. *Int. Manag. Rev.* **2017**, *13*, 22–36. Available online: http://americanscholarspress.us/journals/IMR/pdf/IMR-1-2017.%20pdf/IMR-v13n1art3.pdf (accessed on 12 November 2021).
3. Gess-Newsome, J.A. Model of Teacher Professional Knowledge and Skill Including PCK. In *Re-Examining Pedagogical Content Knowledge in Science Education*; Berry, A., Friedrichsen, P., Loughran, J., Eds.; Routledge: New York, NY, USA, 2015; pp. 28–42.
4. Rockoff, J.E. The Impact of Individual Teachers on Student Achievement: Evidence from Panel Data. *Am. Econ. Rev.* **2004**, *94*, 247–252. [CrossRef]
5. Cheuk, T. Discourse Practices in the New Standards: The Role of Argumentation in Common Core-era Next Generation Science Standards Classroom for English Language Learners. *Elect. J. Sci. Educ.* **2016**, *20*, 92–111.
6. National Center for Education Statistics. *Fast Facts: English Language Learners*; Institute of Education Sciences, U.S. Department of Education: Washington, DC, USA, 2015. Available online: https://nces.ed.gov/fastfacts/display.asp?id=96 (accessed on 12 November 2021).
7. Windschitl, M.; Thompson, J.; Braaten, M.; Stroupe, D. Proposing a Core Set of Instructional Practices and Tools for Teachers of Science. *Sci. Educ.* **2012**, *96*, 878–903. [CrossRef]
8. Banilower, E.R.; Smith, P.S.; Malzahn, K.A.; Plumley, C.L.; Gordon, E.M.; Hayes, M.L. *Report of the 2018 NSSME+*; Horizon Research Inc.: Chapel Hill, NC, USA, 2018. Available online: https://files.eric.ed.gov/fulltext/ED598121.pdf (accessed on 12 November 2021).
9. Collins, J.C.; Porras, J.I. *Built to Last: Successful Habits of Visionary Companies*; Random House: New York, NY, USA, 1994.
10. Ingersoll, R.M.; Smith, T.M. Do Teacher Induction and Mentoring Matter? *NASSP Bull.* **2004**, *88*, 28–40. [CrossRef]

11. Carver-Thomas, D.; Darling-Hammond, L. *Teacher Turnover: Why It Matters and What We Can Do about It*; Learning Policy Institute: Palo Alto, CA, USA, 2017. Available online: https://learningpolicyinstitute.org/product/teacher-turnover-report (accessed on 12 November 2021).
12. Phi Delta Kappa. *The 51st Annual PDK Poll of the Public's Attitudes toward the Public Schools: Frustration in the Schools Teachers Speak Out on Pay, Funding, and Feeling Valued*; Phi Delta Kappa: Arlington, VA, USA, 2019. Available online: https://kappanonline.org/51st-annual-pdk-poll-publics-attitudes-toward-the-public-schools/ (accessed on 12 November 2021).
13. Margot, K.C.; Kettler, T. Teachers' Perception of STEM Integration and Education: A Systematic Literature Review. *Int. J. STEM Educ.* **2019**, *6*, 2. [CrossRef]
14. Swan, D. *Florida's Economy Ranked #48: 2008 Great Recession*; Southeastern Business Association: Jacksonville, FL, USA, 2017.
15. Gonzalez-DeHass, A.R.; Furner, J.M.; Vásquez-Colina, M.D.; Morris, J.D. Pre-service Elementary Teachers' Achievement Goals and Their Relationship to Math Anxiety. *Learn. Individ. Differ.* **2017**, *60*, 40–45. [CrossRef]
16. Johnson, C.C.; Mohr-Schroeder, M.J.; Moore, T.J.; English, L.D. (Eds.) *Handbook of Research on STEM Education*; Routledge: London, UK, 2020.
17. Dieker, L.A.; Berg, C. Collaborative Program Development between Secondary Science, Mathematics and Special Educators. *Teac. Educ. Sp. Educ.* **2002**, *25*, 92–99. [CrossRef]
18. Hackling, M.; Smith, P.; Murcia, K. Talking Science: Developing a Discourse of Inquiry. *Teach. Sci.* **2010**, *56*, 17–22.
19. Gee, J.P. *How to Do Discourse Analysis: A Toolkit*; Routledge: New York, NY, USA, 2011.
20. Hayden, E.; Baird, M.E.; Singh, A. Learning the Words and Knowing the Concepts: An In-depth Study of One Expert Teacher's Use of Language as a Cultural Tool to Support Inquiry. *Literacy* **2019**, *54*, 18–28. [CrossRef]
21. Swan, B.; Duff, P. *Lockheed Martin/UCF Academy: K–8 Program Evaluation Report (Rep. No. PEER-LMA2010.1-Y12S)*; University of Central Florida, Program Evaluation and Educational Research Group (PEER): Orlando, FL, USA, 2019.
22. UCF FACTS. UCF Facts: 2020–2021. 2021. Available online: https://www.ucf.edu/about-ucf/facts/ (accessed on 12 November 2021).
23. Shulman, L.S. Knowledge and Teaching: Foundations for the New Reform. *Harv. Educ. Rev.* **1987**, *57*, 1–22. [CrossRef]
24. Parker, J.; Heywood, D. Exploring the Relationship between Subject Knowledge and Pedagogic Content Knowledge in Primary Teachers' Learning about Forces. *Int. J. Sci. Educ.* **2000**, *22*, 89–111. [CrossRef]
25. Denisova, E.K.; Bell, C.; Covaleskie, K. Evolving the Physics Mindset: Changing Perceptions and Attitudes toward the Teaching and Learning of Physical Science. *Sci. Child.* **2019**, *56*, 74–78.
26. Mills, G. *Action Research: A Guide for the Teacher Researcher*, 5th ed.; Pearson: Upper Saddle River, NJ, USA, 2013.
27. McNiff, J. *Action Research: Principles and Practice*; Routledge: London, UK, 2013.
28. McNiff, J. *Writing and Doing Action Research*; Sage: London, UK, 2014.
29. Nugent, G.; Malik, S.M.Y.; Hollingsworth, S. *Using Action Research to Improve Literacy Instruction in Classrooms around the World: A Practical Guide to Action Research for Literacy Educators*; Global Operations Unit, International Reading Association: Washington, DC, USA, 2012. Available online: https://www.literacyeurope.org/wp-content/uploads/2012/12/a-practical-guide-to-action-research-for-literacy-.pdf (accessed on 12 November 2021).
30. Reason, P.; Bradbury, H. (Eds.) *Handbook of Action Research: Participative Inquiry and Practice*; Sage: London, UK, 2001.
31. Sagor, R. *Guiding School Improvement with Action Research*; Association of Supervision and Curriculum Development: Alexandria, VA, USA, 2020.
32. Nearpod. However You Teach, It's in Nearpod, n.d. Available online: https://nearpod.com/ (accessed on 12 November 2021).
33. Sutcher, L.; Darling-Hammond, L.; Carver-Thomas, D. *A Coming Crisis in Teaching? Teacher Supply, Demand, and Shortages in the US*; Learning Policy Institute: Palo Alto, CA, USA, 2016. Available online: https://learningpolicyinstitute.org/product/solving-teacher-shortage (accessed on 12 November 2021).
34. National Academies of Sciences, Engineering, and Medicine. *Changing Expectations for the K-12 Teacher Workforce: Policies, Preservice Education, Professional Development, and the Workplace*; The National Academies Press: Washington, DC, USA, 2020. [CrossRef]
35. Bybee, R.W. *The BSCS 5E Instructional Model: Creating Teachable Moments*; NSTA Press: Arlington, VA, USA, 2015.
36. Sinatra, G.M.; Heddy, B.C.; Lombardi, D. The Challenges of Defining and Measuring Student Engagement in Science. *Educ. Psychol.* **2015**, *50*, 1–13. [CrossRef]
37. U.S. Department of Labor, Bureau of Labor Statistics. Employment Projections. 2017. Available online: https://www.bls.gov/spotlight/2017/science-technology-engineering-and-mathematics-stem-occupations-past-present-and-future/home.htm (accessed on 12 November 2021).
38. U.S. Department of Education. Return to School Roadmap. 2021. Available online: https://sites.ed.gov/roadmap/?utm_content&utm_medium=email&utm_name&utm_source=govdelivery&utm_term (accessed on 12 November 2021).

education sciences

MDPI

Article

Actualizing Change after Experiencing Significant Mathematics PD: Hearing from Teachers of Color about Their Practice and Mathematical Identities

Richard Kitchen [1],*, Monica Martinez-Archuleta [2], Lorenzo Gonzales [2] and Ali Bicer [1]

[1] School of Teacher Education, University of Wyoming, Laramie, WY 82071, USA; abicer@uwyo.edu
[2] Los Alamos National Laboratory Math and Science Academy, Los Alamos, NM 87545, USA; m.archuleta@lanl.gov (M.M.-A.); lxg@lanl.gov (L.G.)
* Correspondence: rkitchen@uwyo.edu; Tel.: +1-307-766-6377

Abstract: While it is well-documented that students of color and students from low-income communities have often been denied access to a challenging education in mathematics in the United States, less is known about how teachers of color have overcome their deprived educational backgrounds to become teachers of mathematics who implement inquiry-based instructional methods as a means to improve their students' learning and mathematical identities. In this article, we use a sociopolitical theoretical framework to examine how seven elementary school teachers of color characterized their experiences as mathematics students, themselves as teachers of mathematics, and their mathematical identities after experiencing significant professional development in mathematics. All the participants in this study had experienced extensive professional development support in mathematics over a sustained period of time. We demonstrate through the teachers' narratives that, given the deprived mathematics education that the majority of the participants experienced as PK-12 students, having opportunities to participate in significant and focused PD in mathematics over a sustained period transformed how teachers viewed themselves as teachers and positively impacted their mathematical identities.

Keywords: mathematics professional development; teachers of color; mathematical identities

Citation: Kitchen, R.; Martinez-Archuleta, M.; Gonzales, L.; Bicer, A. Actualizing Change after Experiencing Significant Mathematics PD: Hearing from Teachers of Color about Their Practice and Mathematical Identities. *Educ. Sci.* **2021**, *11*, 710. https://doi.org/10.3390/educsci11110710

Academic Editors: Andrea Burrows, Mike Borowczak and Lieven Verschaffel

Received: 1 October 2021
Accepted: 2 November 2021
Published: 4 November 2021

1. Introduction

> 'So I feel like I have gained so much confidence in my own mathematical skills by participating in the Institute because other people recognized that I have something to contribute, that my ideas are worth hearing, and somebody liked it or somebody said, 'Wow, I really liked that model or I liked the way you explained that or I get it because I understand what you're talking about ...' (Gloria, 7th Grade Mathematics Teacher)
>
> 'We were spoon-fed when we were in elementary school . . . You do this, you line your numbers, you borrowed. We didn't know what we were doing. Now, I am creating thinkers, not spoon-feeding, not telling them what to think or how to think. They are discovering their way of learning mathematics.' (Alana, 3rd Grade Teacher)

While it is well-documented that students of color and students from low-income communities have often been denied access to a challenging education in mathematics in the United States [1–3], less is known about how teachers of color have overcome their deprived educational backgrounds and experiences to become teachers of mathematics who use inquiry-based instruction to improve the learning of their students. Historically, students of color and students from low-income communities generally attend schools with high percentages of novice teachers who are not well prepared to teach mathematics [4,5]. Moreover, students of color and students from low-income communities have been largely subjected to instruction as pre-tertiary students that emphasized the memorization of math facts, algorithms, procedures, and mathematical rules [6–8]. To overcome this legacy, teachers of color and teachers who come from low-income communities need significant professional development opportunities [9] to learn the specialized mathematical knowledge needed by teachers [10] and to learn how to use dynamic instructional formats [11,12].

The opening narratives are from teachers who experienced extensive professional development (PD) support in mathematics over a sustained period of time. In this article, we use a sociopolitical theoretical framework to examine how these teachers and five other elementary school teachers of color characterized their experiences as pre-tertiary mathematics students, and how they characterized themselves as teachers of mathematics and their mathematical identities after experiencing extensive professional development in mathematics. The research questions that we address are the following:

1. How do elementary school teachers of color characterize their experiences in mathematics as pre-tertiary students?
2. How do these teachers characterize themselves as teachers of mathematics after experiencing significant mathematics professional development?
3. How do these teachers characterize their mathematical identities after significant PD experiences in mathematics?

Based on the teachers' narratives, we demonstrate that, despite the deprived mathematics education that the participants experienced for the most part as pre-tertiary students, having opportunities to participate in significant and focused PD in mathematics over a sustained period of time transformed how they viewed themselves as teachers and positively impacted their mathematical identities. First, though, we describe the intensive PD support provided to the seven elementary school teachers, all people of color, over many years. We review pertinent research literature that demonstrates the challenges students of color and students who grow up in low-income communities must overcome to become effective teachers of mathematics. We also review the literature on mathematical identity.

1.1. An Overview of the Institute

Every academic year since 2009, the Los Alamos National Laboratory Math and Science Academy, (MSA has offered professional development sessions, referred to collectively as the "Institute", for primary and secondary-level teachers of mathematics who teach in culturally and linguistically diverse rural schools in northern New Mexico, USA. ("Culturally and linguistically diverse" (CLD) is used here as synonymous with people who are members of racial minority groups in the United States, also referred to as "people of color.") The Institute includes six full-day sessions and a week of full-day summer sessions. The primary goals of the Institute are to support participating teachers to learn the specialized mathematical knowledge needed by teachers through problem solving, to learn about inquiry-based instruction by experiencing such instruction first-hand, and to experience being members of a community of practice in which respect for the dignity of participants is paramount. In the Institute, teachers consistently solved problems, shared their mathematical solutions in small and whole groups, and had opportunities to examine other teachers' mathematical ideas. The design of the Institute was driven by our collective belief that through experiencing inquiry-based instruction first-hand as learners participating teachers would learn of the benefits of such instruction (e.g., the value of eliciting students' ideas as a means to engage in mathematical discourse and enhance participants' mathematical identities) and would want the same for their own students [9]. In addition to the Institute, MSA provides job-embedded professional learning for teachers in their classrooms that includes student-centered coaching, modeling, and lesson observations with debriefings. The continuous contact and collaboration with teachers offer the MSA staff an advanced realization of what teachers need to improve their mathematics instruction. The unofficial motto of the MSA staff is "El trabajo te dice que hacer," which translates as, "The work tells you what to do" to support the needs of teachers of mathematics. In this article, we primarily focus on how the Institute affected participants' teaching and mathematical identities, though participants also alluded to how their participation in MSA as a whole impacted them in the interviews conducted.

The vast majority of Institute participants are women and people of color, primarily of Spanish and Native American descent. As pre-tertiary students, most participants attended schools in northern New Mexico where they were largely subjected to years of rote instruction in which they were expected to memorize math facts, algorithms, and mathematical procedures [7]. To counteract their past impoverished experiences in mathematics, participants regularly engaged in solving mathematically-rich, thought-provoking problems during the Institute. Teachers also learned first-hand about inquiry-based instruction, which included jointly producing mathematical ideas with participants as they engaged in reasoning through mathematical modeling to solve problems [13]. A prominent feature of inquiry-based instruction is the value placed upon mathematical conversations or discourse [14]. Through discourse, students have opportunities to make sense of the linguistic complexity of mathematics by listening to and explaining their ideas to others [15].

Another goal was for Institute participants to have ongoing experiences designed to reform their negative mathematical identities. Research on mathematical identity initially considered issues related to motivation to engage in learning mathematics, but has been expanded to include the study of the relationship between learning and students' sociopolitical contexts [16]. Through noticing teachers' ideas [17] and then publicly leveraging these ideas to extend instruction, a goal of the Institute was to send the indisputable message that teachers have valuable mathematical knowledge that needs to be shared with others (i.e., their community of practice). Being a valued member of a community of practice stands in stark contrast to what participants experienced in mathematics classrooms as pre-tertiary students, classrooms in which they were often made to feel mathematically incompetent and even stupid [9].

1.2. Students of Color Lack Access to a Quality Mathematics Education

In the United States, students of color have historically been denied access to a rigorous education in mathematics [2,8,18]. Learning expectations tend to be lower for students of color [19,20] compared to those for middle class and upper-middle class White and Asian students [18,19]. Mathematics instruction in schools that largely serve low-income, students of color tend to focus on computation over conceptual understanding, facts and rules, and memorization over sense-making [7–9]. Such highly authoritarian, skills-based instruction characterized by low expectations was coined the "pedagogy of poverty" by Haberman [21]. In the United States, it is more likely to find such instruction in schools located in communities of color than in schools located in affluent, White communities. The majority of the participants in this study viewed their schooling experiences negatively. Six of the seven teacher participants grew up in low-income, northern New Mexico communities where they experienced intellectual violence; their cultures and languages were either ignored or minimized [22,23]. For Institute participants, experiencing inquiry-based instruction in which their ideas were central and taken seriously was a major departure from the sort of instruction that they experienced in their youth.

1.3. Mathematical Identity

Researchers of mathematical identity have historically considered issues related to student affect such as students' persistence, motivation, and interest in mathematics [24]. Researchers have broadened the notion of mathematical identity to consider relationships among the larger learning environment of the classroom, issues of power, and learning [16,24–26]. Cobb et al. [24] found significant differences between the mathematical identities of students in two classrooms. In a mathematics classroom in which students experienced more traditional mathematics instruction in which learning was largely passive, four of the 11 participants characterized themselves as competent mathematics students. In contrast, all 11 students in another classroom where instruction tended to be more dynamic and inquiry-based viewed themselves and their peers as successful. Teachers who worked to support their students to articulate their solutions to tasks were more apt at helping their students develop positive mathematical identities [24]. One of the primary goals of the Institute is to notice and make the ideas of participants, mostly women of color, a central focus of our work [9]. Ultimately, the hope is that, through positioning participants as competent mathematics students, their mathematical identities will be enhanced. Moreover, after experiencing such instruction firsthand, the hope is that participants will want the same for their students; they will return to the classroom, work to improve their instruction, and centralize their students' ideas as important during instruction.

1.4. Theoretical Framework: Sociopolitical Theoretical Perspective

In this study, we used a sociopolitical theoretical framework, focusing on educational injustices that limit students' learning opportunities [7]. A sociopolitical lens places the social, cultural, and political context of learning in the forefront when examining phenomena such as whether underserved students have access to a problem-solving based mathematics curriculum and instruction [27], how tracking affects students' access to a rigorous mathematics education [28], and how class and race influence mathematics instruction [8,29]. Using a sociopolitical lens, educational policies and practices are considered from the perspective that differential access to educational opportunities is rooted in differences based on racialized and classed experiences [30]. Using a sociopolitical lens in this study, we take it as a given that the vast majority of teachers who participated in the Institute, most of whom were people of color, had generally experienced mathematics education in impoverished formats given their racial/ethnic backgrounds and the fact that they had grown up in low-income communities [9].

2. Materials and Methods

2.1. Research Context and Participants

In this study, we used a grounded-theoretical approach [31] to examine narratives collected from interviews conducted with seven teachers who participated. This process involved examining teachers' narratives to understand how the teachers characterized their experiences as mathematics students, themselves as teachers of mathematics, and their mathematical identities. We interpreted teachers' narratives using interpretative methods [31]. The four authors independently coded each of the seven interviews. Each author also used memoing to make sense of codes they developed and to create themes that emerged in their respective analysis of the narratives.

To address our three research questions, we used purposeful sampling. All seven of the teachers who were interviewed as part of this study participated in the Institute over a significant period of time; two years minimum. The seven were invited to participate in the study because of their extensive participation in the Institute. Table 1 provides information about the participants. The seven participants ranged from 38 to 52 years of age. All hold undergraduate degrees in elementary education, and five (Gloria, Suzie, Alana, Camila, and Silvia) had obtained a master's degree in education at the time the study was conducted. All seven are persons of color; three are Native American and four are Hispanic (The term "Hispanic" is commonly used in New Mexico to denote individuals and communities of Spanish descent). In addition, six of the participants are female and one is male. The number of years of teaching experience of the seven participants ranged from 8 to 22 years.

Table 1. Information about Study Participants.

Pseudonym	Gender Identity	Ethnicity/Race	Role	Years Teaching
Gloria	Female	Hispanic	Middle school math teacher	22 years
Suzie	Female	Hispanic	4th grade teacher	8 years as teacher, 7 years as teaching assistance
Alana	Female	Native American	3rd grade teacher	21 years
Camila	Female	Hispanic	5th grade teacher	21 years
Silvia	Female	Native American	2nd grade teacher	15 years
James	Male	Native American	4th grade teacher	14 years
Adriana	Female	Hispanic	6th grade math teacher	13 years

2.2. Data Collection

We conducted semi-structured interviews with the seven participating teachers via Zoom during the Spring 2021 semester. Each interview lasted between 60 and 90 min and was recorded. The primary purpose of the interviews was to learn how the teachers characterized their experiences as mathematics students, and themselves as teachers of mathematics and their mathematical identities after experiencing significant professional development in mathematics. The interview questions are listed in Appendix A.

2.3. Data Analysis

We used a sociopolitical lens to analyze the seven participating teachers' narratives. Specifically, we used interpretive methods [31] to examine the interplay among the teachers' narratives and the social, cultural, and political context of teaching mathematics in northern New Mexico. Each member of the research team independently reviewed each interview and then engaged in a process of open coding of the interviews. Subsequently, the research team met on two occasions via Zoom to engage in an iterative process of coding, reflecting upon, and then clarifying, teachers' narratives [32]. At the conclusion of this process, the research team decided to focus on three research questions because of our collective belief that these questions provided important insights about changes in teachers' mathematical identities after their intensive participation in the Institute.

2.4. Ethical Considerations

Ethical approval for this research project was granted through the University of Wyoming's IRB and written consent by each interviewee. To maintain anonymity, pseudonyms are used for participating teachers.

3. Results

We organize our findings from the interviews to align with the three research questions as follows: (1) How the teachers characterized their experiences in mathematics as pre-tertiary students, (2) how teachers characterized themselves as teachers of mathematics after experiencing significant mathematics professional development, and (3) how teachers characterized their mathematical identities after significant PD experiences in mathematics.

3.1. How the Teachers Characterized Their Experiences in Mathematics as Pre-Tertiary Students

Participants shared their experiences of their own mathematics learning as pre-tertiary students. In the discussions we had with teachers, they shared significant challenges that they had faced as part of their pre-tertiary education in mathematics. Adriana, who had taught upper elementary students in northern New Mexico her entire career, remembered learning procedural ways of solving mathematics problems and was quite good at following procedures. Such instruction places more emphasis on computation than conceptual understanding, memorization of facts, and instruction of rules [7–9]. She explained that she was not necessarily interested in learning why procedures worked:

> 'When I was in high school, I was taught the procedural way and it worked, and I thought I was good. And I thought I would be great teaching that to other students and it didn't work. In college I was pushed to learn the conceptual way and I resisted it a lot. So I stayed in that same mindset in college, because I didn't have the real life experience to know that the procedural way didn't work for everybody. So I resisted that change. I resisted that idea, that change, that math identity change until I went into the real world. And I noticed then that doing math procedurally didn't work, but that's what I was taught. That's how I could do it.'

Through her experiences in the classroom, Adriana came to realize that if she wanted to help her students learn mathematics, she needed to learn other ways of teaching mathematics. Ultimately, she came to appreciate the need to change her teaching style and her identity as a mathematics learner. Adriana came to believe that she could help more students by having a better grasp of why procedures work, and that, through this understanding, students will be better prepared to be successful in future mathematics coursework.

Three teachers reported that drawing models and using manipulatives in the early grades helped them concretely understand mathematical concepts, but drawings and models were not utilized in the later grades. James, a teacher with experience teaching in public elementary schools, but who was teaching at a Bureau of Indian Education (BIE) elementary school when this interview took place, explained, "I'm one who has to draw a model. I have to, I have to go there first. I have to make sense of the problem, and draw some kind of model. From a model I can move into an equation and then an explanation." James continued by sharing that he struggled to understand subtraction and that models were not provided for him to help him understand subtraction. He described how the procedure was emphasized over understanding:

> 'One thing that I remember as an elementary student was when it came to subtraction, I never understood. I don't know if it was just the way it was explained to me, just that procedural process. Like when it came to subtracting zeros, the whole regrouping, I did not understand that process at all.'

James tried to tell his teachers that he did not understand what the process of "borrowing" was and why it worked, but felt ignored and was pushed to move on. He was told, "Just do it. That's how it's done." He came to realize that the teacher probably did not understand regrouping himself or did not know another strategy for subtraction. This was a common experience among the participants; teachers most likely did not understand underlying concepts themselves and so they taught mathematics in a procedural manner in which the emphasis was on mimicking the teacher's procedure.

Other teachers in this study shared how being placed in low level mathematics classes hurt their mathematical identities. Gloria, who had taught a range of grade-levels in New Mexican elementary and middle schools, struggled to see herself as a mathematics learner. She shared her experience of being placed in a remedial mathematics class in junior high school.

> 'When I got into junior high, I was placed in the lowest math class there was. So right there, I was like, oh, well, I'm really bad. I must really be bad at math if I got placed here. So, I guess that my math identity began. I thought I'm not good enough. I'm not smart enough. I don't get it, and so I was afraid. When I entered college, I knew I wasn't going to take high level math classes and tried to avoid anything that had to do with math.'

Silvia, a teacher who had taught both 2nd and 4th grade at a BIE Pueblo elementary school in northern New Mexico, shared her experience of being placed into a "math lab" (remedial) class in middle school. Despite loving mathematics in the early elementary grades, Silvia had difficulty with fractions and decimals and was placed into the math lab, a remedial class in middle school.

> 'When I tested into the general math class, one of my classes ended up being a math lab. So it was kind of like the extra help that I needed. So I had two math classes. One was the regular math class and then a math lab. I would go to the math lab and I was getting worksheets. There'd be instructions on what to do. A lot of it was like percents, decimals and fractions. It was kind of a way for me to catch up, but I had to kind of catch up on my own because there wasn't real direct instruction. It was more like worksheets and going at your own pace.'

Silvia's experience in the math lab was much like what many students of color have historically experienced in U.S. schools; traditional instruction focused on memorization and procedures [7,8]. Moreover, Silvia's mother did not know how to advocate for her to have access to a more challenging mathematics curriculum when she was in school: "I didn't really understand all of that at that moment. I didn't really understand. My mom didn't understand the kind of level of math that I should be at." While Silvia spent 7th grade year in the general mathematics class, other students were taking pre-algebra. Fortunately, Silvia had an advocate in her 7th grade math teacher; the teacher recommended she be placed in algebra in 8th grade. Silvia shared the experience of being placed in algebra without having a strong foundation in pre-algebra:

> 'In eighth grade, teachers were seeing that I was understanding. So, they bumped me into algebra. I went into Algebra I because that's where they said I should be, but I didn't have the pre-algebra foundation that I should have gotten in 7th grade. I was always trying to catch up. I still always struggle with fractions and percents and decimals, because I never really had instruction (in these areas).'

After graduating from high school, Silvia wanted to pursue a degree in environmental science. As an undergraduate at one of the most prestigious universities in the United States, Silvia quickly learned that she was unprepared for the rigors of college mathematics. Given her experiences in middle and high school, Silvia knew that she was not well prepared and was discouraged from continuing the science degree she sought. She shared,

> 'I just didn't feel prepared. Even though I had taken calculus in high school, I just didn't feel prepared. So that was kind of discouraging. And for me, that was a feeling of, I did not belong at my school, because I was not smart enough to get through those classes. So, I dropped the classes.'

These negative mathematics experiences changed her college path. Silvia began taking classes in social justice and focused on comparative studies in race and ethnicity. She was later advised to consider the education program since she had shown a passion for the future of her community.

Camila, a teacher who had taught upper elementary grades in New Mexico public schools for her entire career, shared that mathematics made sense to her in elementary school since she was allowed to use models, charts and drawings. However, that all changed in middle school as students were expected to learn mathematics using only procedures. Since she could memorize steps and procedures, mathematics classes were easy for her. Nevertheless, Camila came to realize that she did not have a strong understanding of mathematics. In middle school, Camila could solve problems by following procedures that she had been taught, but rarely understood why the procedures worked:

> 'So I get into middle school and it was the same thing (solving problems using procedures we had been taught). Why do I have to do this? And it was always because that's just what you do it. I could follow procedures left and right. I could solve anything. I could memorize procedures. But a lot of times I just wouldn't do my work because I thought, why am I going to have to do 50 problems using the same procedure when I already know how to do it? And I don't really understand why I'm doing it. That cycle continued through high school . . . I

> remember really depending on my dad to help me make connections from what I was doing in school and how they would be applied in the real world.'

The experiences teachers shared in their early learning of mathematics were quite similar. They rarely shared experiences in which they felt successful in learning mathematics in the early grades. In addition, their experiences in secondary mathematics illustrate that they were generally not supported to experience mathematical success. Many of the teachers' narratives demonstrate that their teachers rarely helped them make sense of why the mathematical procedures and algorithms they were taught worked. Their understanding of mathematical concepts was fragile and limited their capacities to succeed in future mathematics courses.

3.2. How Teachers Characterized Themselves as Teachers of Mathematics after Experiencing Significant Mathematics Professional Development

Teachers expressed how their participation in the Institute, which some had participated in it for over 10 years, had positively impacted their understanding of the mathematics they taught. Silvia credited her 11-year connection to the Institute with being able to "see" fractions as a division operation. She recalled her surprise at being able to clearly understand an oral explanation that provided insight about how 24/8 is equivalent to 24 divided by 8 and how this insight contrasts with simply applying the traditional algorithm of 24 ÷ 8 to derive the solution of 3. Silvia also described insights derived from examining how 25/8 = 24/8 + 1/8 = 3 1/8 as compared to simply applying the traditional algorithm of 25 ÷ 8 = 3 R 1. She explained:

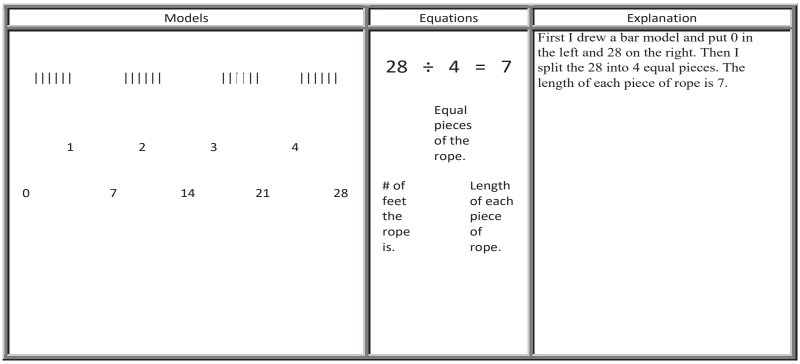
> 'He wasn't writing it out, he wasn't showing it. He was just verbally saying it, and I could totally follow and understood everything that he was saying. And so, then I thought about it later and (asked myself) could I, a few years ago, have followed and understood that conversation? I guess it's obvious that you've grown in your understanding of math.'

Six of the seven teachers expressed less confidence in their abilities to teach mathematics two grade levels above the highest level they had previously taught. In addition, sixth-grade mathematics and algebra, the "gatekeeper" to other STEM fields and college success [33], presented a challenge for most of the teachers. For example, Silvia revealed, "But sixth grade, like watching what Freddy (the sixth-grade teacher) does and seeing the level of sixth-grade math, I just feel like, I don't know that I could do that." James was anxious about algebraic equations, but was comfortable teaching fourth grade: "I could teach it (fourth grade) in my sleep. I would like to build a deeper understanding of mathematics going back to algebra and algebra II . . . I think there's a way for me to really see algebra in a different way than I've never seen before, where it's more conceptual rather than abstract." Gloria felt confident in her abilities to teach seventh-grade mathematics, the grade she was teaching. However, she echoed James' anxiety about algebra:

> 'As far as my math teaching, I think what has helped me is my confidence in my math skills and my understanding has improved so that I can help students that have difficulty. I'm not yet confident in teaching algebra, if I went above where I'm at right now, I think it would be a little scary for me, like high school math.'

As part of their experiences in the Institute, teachers experienced inquiry-based instruction that was designed to pique their curiosity as they solved challenging problems and were asked to explain and justify their mathematical thinking [34,35]. Alana, a BIE teacher at a northern New Mexico Pueblo elementary school, had incorporated the Institute's inquiry-based model in her teaching style. "So, I think that was one of my biggest takeaways from the Institute, choosing student work, having them present, and even the progression of how to present so that all the kids can understand using different models." The progression that Alana is referring to are the five practices that Smith and Stein [36] identify that teachers can use to help orchestrate productive mathematical discussions, practices that were modeled for the teachers during the Institute. Alana also had her students “section their notebooks into three sections. They have to show me a model. They have to come up with an equation that connects to the model and the problem. They label their equation and explain the model they use and how they got to their answer.” In Figure 1, an example is given that demonstrates how students in Alana’s class created models, equations, and explained how to solve the following task:

Ms. Yost has a rope that is 28 feet long? She would like to cut the rope into 4 equal pieces. What is the length of each piece of rope? Use models, numbers, and words to communicate your mathematical thinking.



Models	Equations	Explanation
	28 ÷ 4 = 7	First I drew a bar model and put 0 in the left and 28 on the right. Then I split the 28 into 4 equal pieces. The length of each piece of rope is 7.

Figure 1. Alana’s students provide models, equations and explanations to solve a task.

One of the essential features of the Institute that teachers reflected on was how they regularly shared their mathematical ideas with their peers during sessions. Many teachers were not initially comfortable sharing their ideas during the first Institute sessions they attended; they worried that they could make mistakes or that their level of mathematical understanding would be judged negatively by others. After a couple of sessions, though, teachers felt safe and shared their ideas more freely with others. One of the most commonly shared experiences that teachers transferred from the Institute to their instruction involved learning how to support students to generate their own mathematical ideas, share their ideas with others, and compare and contrast these ideas. For example, Gloria said, “Um, having that time to, to view other people’s work, to have them explain it, to ask questions, to make those connections. And being able to explain my own thinking has built up my confidence in my own math skills.”

Teachers also discussed how working in an environment in which it was okay to make mistakes was another feature of the Institute that improved their motivation to want to learn new mathematical ideas. Moreover, teachers shared how working in a safe and collaborative environment during the Institute validated their own thinking and helped them build their confidence in their abilities to do mathematics. Suzie, a 4th grade teacher who also had significant experience as a teaching assistant, shared:

> ‘You feel that you can do math, you know, you feel like you’re validated in your thinking and your confidence, even if it’s in one little aspect of mathematics, you’ve owned it. I don’t say did it correctly because it’s not about doing something correctly. It’s about an idea, a strategy that can lead to an answer, and it may not necessarily be the right answer in the end, but your strategy got you to that point. And your way of thinking got to that point. So yeah, the confidence that you get from that math identity, whenever you, you feel like you did it . . . So, that creates that confidence.’

Suzie added that “when the Institute instructor allows us to speak up about our strategies, our procedures, and the way we’re thinking, we become stronger math educators. We tend to see our misconceptions and correct them in a safe environment.” Suzie also shared how her experiences as a learner in the Institute had impacted her instruction:

"asking students to explain their mathematical thinking has been a real big shift in my experience. It's also helped me be able to grasp those concepts a little stronger as I'm teaching them." Teachers must have strong conceptual mathematical understandings to be able to teach mathematics for understanding [10,37].

Gloria's take-aways from the Institute concerned the importance of collaborative discussions and mathematical modeling that she had integrated into her teaching style. Her biggest takeaway was her burgeoning questioning techniques that promote students in deriving mathematical insights and learning on their own. Gloria explained: "Show me, show me, you know, show me what you're thinking, draw it out, draw a model. This is something I've completely learned through the Institute." We have found that after teachers participate in the Institute for an extended period of time, many have begun to mimic the instructor's teaching moves in their classrooms and to develop their style of inquiry-based lesson delivery.

When Adriana first attended the Institute, she was "really stuck on the procedural, throwing those numbers out there, getting it done. That's what I was taught." The Institute pushed Adriana to think differently, "I think that's what made me a successful teacher, understanding that students needed to know the why behind the math and understand the concepts, rather than just knowing a procedure and memorizing a procedure." Adriana, like the other teachers, came to the understanding that to help students become mathematical thinkers, they needed to become mathematical thinkers themselves:

> 'I've really brought kids out of their shell and had them think about mathematics in a way that they hadn't thought about it before. I got them communicating with each other, sharing ideas, writing down their mathematical thoughts when they really couldn't even express them in the beginning of our mathematics class. And just opening those conversations about why does the math work, what is the concept behind the procedure? I think I really opened up their mind to a world of mathematics that they hadn't really been exposed to before. I think that's what really made me successful is understanding that students really needed to know the why behind the math and understand the concepts rather than just knowing a procedure and memorizing a procedure.'

In addition to working to help their students understand mathematics, teachers wanted their students to experience mathematics in ways that they never had as pre-tertiary students. Specifically, as demonstrated in Adriana's narrative, teachers wanted students to learn how to communicate their mathematical ideas and to ultimately come to see themselves as capable mathematics students.

3.3. How Teachers Characterized Their Mathematical Identities after Significant PD Experiences

During the interviews, teachers made an explicit connection between their students having conceptual mathematical understanding and developing positive mathematical identities. They made this connection through reflecting on their experiences as learners in the Institute. For instance, the teachers described how their confidence in their abilities to do mathematics increased during the Institute by studying patterns and relationships found in mathematics rather than through memorizing unconnected facts and procedures. Adriana shared how focusing on developing her students' conceptual understanding helped her students achieve better results on standardized tests while also positively impacting their mathematical identities:

> 'I think that's what led to their, um, huge gains on the standardized assessments because they could write a paragraph about how they completed a mathematical problem. And it wasn't the steps. It wasn't the procedures, it was the concepts. So, yeah, I saw a lot of students change throughout time and I'm seeing it even now that I'm teaching fifth grade. I've only had these students for four weeks . . . their mathematical identities have changed significantly already.'

Teachers provided specific information about how to develop the conceptual understanding of their students based on what they had learned during the Institute. They noted how during the Institute they were regularly asked to solve problems through applying mathematical modeling such as drawings, manipulation, and a variety of representations. For example, Adriana shared her growth from teaching for procedural understanding to teaching for conceptual understanding:

> 'I was exposed to that conceptual math and look at the concept behind the math. Instead of just the procedure, understand what the problem's asking you to find and think about it deeply so that you can come to an understanding and figure it out instead of just looking for the clues. I was able to change the mathematics program there at the middle school to something that was more conceptual based. Um, so that was kind of a win for me because I had been doing a lot of work with them to kind of see that conceptual side of the mathematics. And there are a lot of great strategies that we've talked about over all the different professional developments that we had together.'

The teachers had the opportunity to develop positive mindsets about mathematics through their participation in the Institute over an extended period of time. As discussed previously, they incorporated some of the instructional strategies learned during the Institute so that their students could also develop positive mindsets about mathematics and develop positive mathematical identities. The participating teachers demonstrated growth mindsets in mathematics when they stated that they could learn mathematics with the necessary time, guidance, and effort. For example, Suzie shared:

> 'I've been able to experience for myself in the Institute that, that growth mindset of like, I don't get it yet right now. I don't get it right now, but I will through practice and through discourse and through experiences that I have with colleagues, you know, the way he groups us, the way he has us discuss our math thinking, and then being able to show our math thinking builds that concrete, representational and abstract in my mind. And that's what builds that, that confidence, I think.'

Generating their own ideas and strategies for solving problems in a community of practice while hearing others' ideas and perspectives validated teachers' ideas and led to improved motivation to learn mathematics. Adriana discussed how her experiences participating in the Institute led her to develop a positive mathematical identity and she transferred these experiences into her classroom as outlined in the following:

> 'I'm not sure that I would have been able to create that mathematical identity that I've created within myself, um, by myself, because I don't know that I would have been able to understand how to do all that stuff or how to teach conceptually, how to learn conceptually. It really was a matter that I learned myself and then I taught it to my students. So if I didn't have that support when I first came out of college ... I don't think I would be as successful as I am . . . I really saw their mathematical identity changed significantly from when I got them in fifth grade to when they left in sixth grade . . . And I think that's what led to their huge gains on the standardized assessments, because they could write a paragraph about how they completed a mathematical problem. And it wasn't the steps. It wasn't the procedures, it was the concepts.'

The Institute also helped teachers come to understand the importance of productive struggle as a means to positively impact students' mathematics identities. During the Institute, they felt like they were the students, and understood better how students could feel and how they could encourage their students to engage in solving mathematical problems. For example, Suzie talked about how through experiencing productive struggle firsthand, her confidence in mathematics improved:

> ‘I got to say that that’s still not enough because I still get pushed to my limits with my, um, productive struggle. And with my productive struggle, I learned so much more of myself and I become more confident and I can build that mathematical identity for my students through that productive struggle in my own classroom.’

Camila shared how through productive struggle her confidence in teaching mathematics was positively impacted:

> ‘I think some of my strengths are that, you know, I allow my students to struggle. I know that has been difficult for me because it’s difficult to see them struggle. And many times I want to jump in and I want to save them right. I want to say, no, no, no, no, no, no, no, no, this is what we have to do. But you know, I have learned that struggle is very important. I also think a strength that when I’m teaching, I don’t do all the talking.’

Teachers shared how their connection with MSA staff during and after the Institute led them to be interested in learning new mathematical ideas and held them accountable for continued mathematical learning. For example, Gloria said:

> ‘I really enjoy, um, even still having that connection. So having [MSA staff] come in and, um, share a book or send an email that says, ‘Oh, you know, look at this.’ Or, you know, like to me, I feel like that still is that accountability. Like it still holds me accountable for I’m continually learning. Like I’m still improving in my math instruction.’
>
> Gloria shared:
>
> ‘Had I not had the support of MSA and the Institute, I’m not sure that I would have been able to create that mathematical identity that I’ve created within myself, by myself, because I don’t know that I would have been able to understand how to do all that stuff or how to teach conceptually, how to learn conceptually, because it really was a matter of that I learned myself and then I taught it to my students. So if I didn’t have that support, when I first came out of college and I’ve got into the real world and I knew that it didn’t work, I don’t know. I don’t think I would be as successful as I am.’

These narratives point to the sustained support that teachers, particularly teachers of color need from high quality PD in mathematics to overcome the crippling effects of an impoverished pre-tertiary mathematics education. These supports included the Institute and, as reflected in their narratives, job-embedded professional learning provided by MSA staff in participating teachers’ classrooms.

4. Discussion

In this study, we examined how seven elementary school teachers of color characterized their experiences as mathematics students, and how they characterized themselves as teachers of mathematics and their mathematical identities after experiencing significant professional development. Considering the first research question about how the teachers of color characterized their experiences in mathematics as pre-tertiary students, the teachers shared challenges that they faced as mathematics students. For instance, some expressed how in their early schooling experiences they had mathematical questions that were often ignored by their teachers. Teachers conjectured that most likely their teachers lacked conceptual understanding themselves, so they taught mathematics in a procedural manner similar to how they had been taught. Teachers also shared how their mathematical identities had been negatively affected through being placed in low level mathematics classes. Adriana was an outlier in this regard; she was a high-achieving mathematics student and wanted to teach mathematics at the middle school level. Although some participants reported having some positive early elementary mathematics learning experiences, things changed as they moved into later grades. Specifically, participants reflected on how they were taught mathematics with little conceptual understanding. Moreover, because of their inadequate preparation in mathematics, teachers' capacities to pursue more advanced mathematics coursework and careers involving mathematics were limited.

With respect to the second research questions, we learned that significant and sustained participation in the Institute had positively impacted teachers' mathematical knowledge, helped them learn how to incorporate inquiry-based instruction in their classrooms, and influenced teachers to want to offer similar instruction to benefit their students. The example provided by Silvia exemplifies how teachers' mathematical knowledge had become more flexible through their experience in the Institute. Moreover, through their experiences in the Institute, they learned about the importance of understanding why particular algorithms and procedures worked. In addition, they learned that through sharing their mathematical thinking with one another, they were able to further develop their mathematical thinking while learning how to justify it. Teachers also discussed the value of using purposeful questions [38] with their students to press students to continually develop their explanations. Lastly, after experiencing mathematics in new and exciting ways, participating Institute teachers wanted their students to experience mathematics similarly. While differences existed among the teachers based on their abilities and willingness to incorporate inquiry-based instruction in their classrooms, the teachers' narratives provide tangible examples of how their instruction had changed for the better based upon their participation in the Institute.

Regarding the third research question, teachers noted how their mathematical identities had been positively affected because of specific features of the Institute. In particular, they noted the importance placed in the Institute on teacher ownership of mathematical ideas or perspectives and how these ideas were compared and contrasted to further enhance teachers' mathematical knowledge. Teachers pointed to the value of creating a safe learning environment for their students in which students could make mistakes without fear of reprisals. Based on their experiences in the Institute, the teachers' believed that their students could be successful in mathematics with the necessary guidance and support, just as they had experienced success in the Institute. Through their experiences in the Institute, teachers developed positive mathematical identities and were continually changing their instruction so that their students could develop more confidence in their mathematical abilities and an interest in mathematics. Lastly, the teachers gave credit to MSA staff who validated their professionalism while holding them accountable for their continuous learning through the classroom-level supports that MSA provided teachers.

From a sociopolitical perspective, the teachers lack of access to a challenging education in mathematics was not coincidental, but reflects the teachers' racialized and classed experiences as pre-tertiary students [30]. The teachers grew up in communities of color and attended schools where their teachers were not generally prepared to teach mathematics for understanding, given that many of them had experienced impoverished mathematics instruction themselves as PK-12 students [9]. Schools located in low-income urban and rural communities of color face similar challenges as northern New Mexican schools. These schools often employ elevated percentages of novice teachers who are generally not well prepared to teach mathematics [4,5]. Moreover, teachers at schools located in low-income, communities of color often lack the skills and expertise needed to engage their students in a rigorous education in mathematics [2,8,9]. Through providing teachers of color ongoing access to inquiry-based instruction and problem solving in which their ideas were front-and-center, the Institute gave the teachers opportunities to learn first-hand the benefits of such instruction as a means to combat historical injustices that they had experienced as pre-tertiary students so that they could be empowered to do the same for their students.

We argue that the sort of rigorous and sustained mathematics PD that is offered through the Institute and the MSA in general needs to be a national priority, particularly at this historic moment of reckoning in the United States with the nation's racist past and structural racism that has normalized educational injustices. Teachers who teach in schools situated in low-income communities of color have unique professional needs. They need access to deep and sustained mathematics PD to overcome the historic legacy of racism in the United States, which has resulted in low-income students of color being denied access to a challenging education in mathematics. Even teachers such as Silvia who had graduated from a prestigious U.S. university have benefitted from attending the Institute over many years; Silvia's pre-service teacher education program was not sufficient to prepare her to learn the specialized mathematical knowledge needed by teachers [10], nor did it prepare her to use dynamic instructional formats [13] such as inquiry-based pedagogy. In summary, high quality mathematics PD needs to be targeted for schools located in communities where high percentages of teachers experienced an impoverished education in mathematics as a means to overcome the historic legacy of racism in the United States.

A limitation of this study is that only seven teachers who had participated in the Institute participated in the study. There were teachers who participated in the Institute who were not as profoundly influenced by their participation in the Institute as these seven teachers. It is important to highlight, though, that these seven teachers had all participated in the Institute for a significant period of time and all had classroom-level supports provided by MSA for four years or more. This points to an important implication of this study: To have a significant impact on the specialized mathematical knowledge of teachers of color who have experienced an impoverished mathematics education, teachers must have consistent and ongoing access to professional development in mathematics. In our view and based upon the teachers' narratives, this PD should have a dual focus on developing teachers' mathematical knowledge, specifically the knowledge they need for the grade level they teach, and providing teachers with opportunities to experience inquiry-based instruction first-hand. The teachers also pointed to the importance of being part of a community of practice in which they could get help when needed. As teachers' specialized mathematical knowledge [10] is developed in a supportive community, they experience mathematical success and the joy of doing mathematics with their peers. Subsequently, the teachers' mathematical identities are also enhanced [9]. Another limitation of this study is that our findings are based solely on teachers' narratives, and we were not able to triangulate our findings with classroom observations. Thus, we were not able to corroborate teachers' declarations about how the PD had affected their practices, their mathematical identities, and their students' identities.

The Institute intentionally targeted breaking the cycle of poorly prepared teachers teaching mathematics in an impoverished manner by simultaneously focusing on improving teachers' specialized mathematics knowledge and having the teachers experience inquiry-based instruction directly in a community as a means to inspire them to see the benefits of employing such instruction for their students [9]. As teachers develop more positive mathematical identities, they want the same for their students. Consequently, by intentionally offering teachers long-term access to high quality mathematics PD, the generation of students that the teachers teach will have opportunities to learn challenging mathematical content and develop positive mathematical identities themselves thus breaking an historical cycle.

Author Contributions: Conceptualization, R.K., M.M.-A. and L.G.; methodology, R.K. and M.M.-A.; validation, M.M.-A., L.G. and A.B., formal analysis, R.K., M.M.-A., L.G. and A.B.; investigation, R.K., M.M.-A., L.G. and A.B.; data curation, R.K., M.M.-A., L.G. and A.B.; writing—original draft preparation, R.K.; writing—review and editing, R.K., M.M.-A., L.G. and A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Wyoming (protocol code #20210202RK02939, date of approval 2 February 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Individual Teacher Interview Protocol

(1) How many years have you been teaching?
(2) What grade level are you currently teaching?
(3) What grade levels have you taught and where have you taught?
(4) When you think back about your successes as a math teacher, what are those successes? PROBE: Based on the teacher's response, ask questions to elicit specific information related to a success or successes that the teacher names.
(5) How would you generally characterize your experiences in math in grades K-12? Can you share a story with us about something that happened to you as a math student that really impacted you in a big way? PROBE: Based on the teacher's answer, ask specific probe questions such as: "You said that your experiences in math were good in the elementary grades, but not so great in high school. What made your math experiences in the elementary grades better than your math experiences in high school?" OR "You just shared that not so happy story with us about what happened to you in Algebra class in high school. How has that impacted the way you approach teaching your students math?" etc.
(6) Can you tell us about the math content courses that you took in your teacher education program? How many courses did you take and did these courses help prepare you to be an effective teacher of mathematics?
(7) How would you characterize yourself as a math teacher? What are your greatest strengths as a math teacher and what areas of your math teaching would you'd like to improve in? PROBE: Could specifically ask about the teacher's beliefs about math teaching. For example, ask: "What teaching strategies do you use to help students learn math?"
(8) How comfortable are you understanding the math concepts typically taught at your grade level? How about math concepts typically taught a grade level or two above the grade you teach?
(9) What are some reasons you might hesitate to implement something new in math? For example, you have participated in the Institute for the past ___ years. In those sessions, you have learned about inquiry-based instruction that involves actively engaging students in math lessons. Have you tried to implement ideas related to inquiry-based instruction with your students? Why or why not? PROBE: What are some challenges you have faced associated with implementing inquiry-based instruction in your math classes? What have you done to help you feel prepared to implement inquiry-based instruction? What sort of supports do you need to use inquiry-based instruction in your math classes?
(10) In the Institute, one of the goals has been to demonstrate the value of including participants' mathematical ideas in instruction. As you may recall, participants are regularly called on to share and explain their solutions to problems in both small group and whole group. A reason to do this is to help participants realize that they have wonderful math ideas that need to be shared with their peers. Hopefully, this leads to participants developing positive mathematical identities. Can you talk about your mathematical identity and how your participation in the Institute has impacted your mathematics identity? PROBE: What challenges have you found may be associated with you having a positive mathematical identity? What sort of supports do you need to have a positive identity as a math teacher?
(11) How important is it to you that your students develop a positive mathematics identity? What are some practical strategies that you use to help your students develop a positive mathematics identity?
(12) We've discussed challenges that you've faced to change your instruction to be more inquiry-based. If we haven't already discussed it, can you talk about your interest in potentially changing your instruction in these ways? What supports exist in your

district or school to try and change your instruction in these ways? POTENTIAL PROBES: How important is it to you to change your instruction in these ways? How might you and/or your students benefit from making these instructional changes?

(13) We've discussed challenges that you've faced to have a more positive mathematical identity. Is there anything that you'd like to add to this conversation that we haven't already discussed?

(14) Is there anything that you'd like to add to our conversation about your experiences in the Institute and potential challenges/barriers you've faced to change your math instruction?

References

1. Aguirre, J.; Herbel-Eisenmann, B.; Celedón-Pattichis, S.; Civil, M.; Wilkerson, T.; Stephan, M.; Pape, S.; Clements, D.H. Equity Within Mathematics Education Research as a Political Act: Moving From Choice to Intentional Collective Professional Responsibility. *J. Res. Math. Educ.* **2017**, *48*, 124–147. [CrossRef]
2. Kitchen, R.S.; DePree, J.; Celedón-Pattichis, S.; Brinkerhoff, J. *Mathematics Education at Highly Effective Schools that Serve the Poor: Strategies for Change*; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 2007.
3. Leonard, J.; Martin, D.B. *Beyond the Numbers and Toward New Discourse: The Brilliance of Black Children in Mathematics*; Information Age Publishing: Charlotte, NC, USA, 2013.
4. Ingersoll, R.M. Teacher Turnover and Teacher Shortages: An Organizational Analysis. *Am. Educ. Res. J.* **2001**, *38*, 499–534. [CrossRef]
5. Ingersoll, R.M.; May, H. The Magnitude, Destinations, and Determinants of Mathematics and Science Teacher Turnover. *Educ. Eval. Policy Anal.* **2012**, *34*, 435–464. [CrossRef]
6. Davis, J.; Martin, D.B. Racism, assessment, and instructional practices: Implications for mathematics teachers of African American students. *J. Urban Math. Educ.* **2008**, *1*, 10–34. [CrossRef]
7. Kitchen, R.S. Getting real about mathematics education reform in high poverty communities. *Learn. Math.* **2003**, *23*, 16–22.
8. Martin, D.B. Race, Racial Projects, and Mathematics Education. *J. Res. Math. Educ.* **2013**, *44*, 316–333. [CrossRef]
9. Kitchen, R. The power of their ideas: Leveraging teachers' mathematical ideas in professional development. *Intern. J. Math. Educ. Sci. Technol.* **2020**. [CrossRef]
10. Hill, H.C.; Rowan, B.; Ball, D.L. Effects of Teachers' Mathematical Knowledge for Teaching on Student Achievement. *Am. Educ. Res. J.* **2005**, *42*, 371–406. [CrossRef]
11. Loucks-Horsley, S.; Stiles, K.E.; Mundry, S.; Love, N.; Hewson, P.W. *Designing Professional Development for Teachers of Science and Mathematics*, 3rd ed.; Corwin Press: Thousand Oaks, CA, USA, 2010.
12. Sztajn, P.; Hackenberg, A.J.; White, D.Y.; Allexsaht-Snider, M. Mathematics professional development for elementary teachers: Building trust within a school-based mathematics education community. *Teach. Teach. Educ.* **2007**, *23*, 970–984. [CrossRef]
13. Staples, M. Supporting Whole-class Collaborative Inquiry in a Secondary Mathematics Classroom. *Cogn. Instr.* **2007**, *25*, 161–217. [CrossRef]
14. Herbel-Eisenmann, B.A.; Cirillo, M. *Promoting Purposeful Discourse: Teacher Research in Mathematics Classrooms*; National Council of Teachers of Mathematics: Reston, VA, USA, 2009.
15. Kooloos, C.; Oolbekkink-Marchand, H.; Kaenders, R.; Heckman, G. Orchestrating Mathematical Classroom Discourse About Various Solution Methods: Case Study of a Teacher's Development. *J. Math.-Didaktik* **2020**, *41*, 357–389. [CrossRef]
16. Gibbons, Y.M.; Martin, D.B. Mathematics Success and Failure among African-American Youth: The Roles of Sociohistorical Context, Community Forces, School Influence, and Individual Agency. *Contemp. Sociol. A J. Rev.* **2001**, *30*, 407. [CrossRef]
17. Jacobs, V.R.; Lamb, L.L.C.; Philipp, R.A. Professional Noticing of Children's Mathematical Thinking. *J. Res. Math. Educ.* **2010**, *41*, 169–202. [CrossRef]
18. Flores, A. The opportunity gap. In *Promoting High Participation and Success in Mathematics by Hispanic Students: Examining Opportunities and Probing Promising Practices*; National Education Association: Washington, DC, USA, 2008; Volume 1, pp. 1–18.
19. Diversity in Mathematics Education (DiME) Center for Learning and Teaching. Culture, race, power and mathematics edu-cation. In *Second Handbook of Research on Mathematics Teaching and Learning*; Information Age Publishing: Charlotte, NC, USA, 2007; pp. 405–433.
20. Milner, I.H.R. Analyzing Poverty, Learning, and Teaching Through a Critical Race Theory Lens. *Rev. Res. Educ.* **2013**, *37*, 1–53. [CrossRef]
21. Haberman, M. The Pedagogy of Poverty versus Good Teaching. *Phi Delta Kappan* **2010**, *92*, 81–87. [CrossRef]
22. Joseph, N.M.; Smith, A. Black woman first, mathematician second: Toward an understanding of Black women's constructions of mathematics identity. Presented at the 2018 American Educational Research Association Annual Meeting, New York, NY, USA, 13–17 April 2018.
23. Mondragón, J.B.; Stapleton, E.S. *Public Education in New Mexico*; University of New Mexico Press: Albuquerque, NM, USA, 2005.
24. Cobb, P.; Gresalfi, M.; Hodge, L.L. An Interpretive Scheme for Analyzing the Identities That Students Develop in Mathematics Classrooms. *J. Res. Math. Educ.* **2009**, *40*, 40–68. [CrossRef]

25. Boaler, J. The development of disciplinary relationships: Knowledge, practice, and identity in mathematics classrooms. *Learn. Math.* **2002**, *22*, 42–47.
26. Cobb, P.; Hodge, L.L. Culture, Identity, and Equity in the Mathematics Classroom. In *A Journey in Mathematics Education Research*; Springer: New York, NY, USA, 2010; pp. 179–195.
27. Kitchen, R.S. Privilege in mathematics education: Some reflections on Whiteness. In *Interrogating Whiteness and Relinquishing Power: White Faculty's Commitment to Racial Consciousness in STEM Classrooms*; Peter Lang Publishing: New York, NY, USA, 2016; pp. 57–71.
28. Boaler, J. Changing students' lives through the de-tracking of urban mathematics classrooms. *J. Urban Math. Educ.* **2011**, *4*, 7–14. [CrossRef]
29. Gutiérrez, R. A "gap gazing" fetish in mathematics education? Problematizing research on the achievement gap. *J. Res. Math. Educ.* **2008**, *39*, 357–364. [CrossRef]
30. Battey, D. Access to mathematics: A possessive investment in whiteness. *Curric. Inq.* **2013**, *43*, 332–359. [CrossRef]
31. Creswell, J.W.; Poth, C.N. *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed.; Sage Publications: Thousand Oaks, CA, USA, 2018.
32. Miles, M.B.; Huberman, A.M.; Saldaña, J. *Qualitative Data Analysis: A Methods Sourcebook*; Sage Publications: Thousand Oaks, CA, USA, 2013.
33. Edwards, T.G. Some Big Ideas of Algebra in the Middle Grades. *Math. Teach. Middle Sch.* **2000**, *6*, 26–31. [CrossRef]
34. Marshall, J.C.; Horton, R.M. The Relationship of Teacher-Facilitated, Inquiry-Based Instruction to Student Higher-Order Thinking. *Sch. Sci. Math.* **2011**, *111*, 93–101. [CrossRef]
35. Warshauer, H.K. Productive struggle in middle school mathematics classrooms. *J. Math. Teach. Educ.* **2015**, *18*, 375–400. [CrossRef]
36. Smith, M.S.; Stein, M.K. *Five Practices for Orchestrating Productive Mathematics Discussions*; National Council of Teachers of Mathematics: Reston, VA, USA, 2011.
37. Ma, L. *Knowing and Teaching Elementary Mathematics: Teachers' Understanding of Fundamental Mathematics in China and the United States*; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 1999.
38. National Council of Teachers of Mathematics. *Principles to Actions: Ensuring Mathematical Success for All*; National Council of Teachers of Mathematics: Reston, VA, USA, 2014.

education sciences

Article

Becoming a STEM-Focused School District: Administrators' Roles and Experiences

Jeanna R. Wieselmann [1,*], **Gillian H. Roehrig** [2], **Elizabeth A. Ring-Whalen** [3] **and Thomas Meagher** [4]

[1] Department of Teaching and Learning, Southern Methodist University, Dallas, TX 75275, USA
[2] Department of Curriculum and Instruction, University of Minnesota, Minneapolis, MN 55455, USA; roehr013@umn.edu
[3] Education Department, St. Catherine University, St. Paul, MN 55105, USA; eawhalen245@stkate.edu
[4] Owatonna Public Schools, Owatonna, MN 55060, USA; tmeagher@isd761.org
* Correspondence: jwieselmann@smu.edu

Abstract: Science, technology, engineering, and mathematics (STEM) schools and districts continue to emerge, and while some research highlights critical components to be included in STEM schools, there is a need to learn more about the process of becoming a STEM school or district. In this study, we investigated a rural United States school district's development and expansion of its STEM education focus, which started in the years leading up to the district's first STEM school opening in 2012. We addressed the research question: How is a district-wide STEM education vision developed, enacted, and sustained by various administrative stakeholders? We interviewed 11 participants, all of whom had some level of administrative responsibility related to the district's STEM mission, coded interviews based on the critical components of STEM schools, and used narrative inquiry methods to describe the district's STEM transition from these administrators' perspectives. Our analysis revealed that several key critical components were central to this district's STEM mission. These components included elements related to leadership, reform-based instructional strategies, and teachers' professional learning. By focusing on different elements at different times and prioritizing several key components throughout, this district was able to achieve its goal of providing STEM instruction to all of the elementary and middle school students.

Keywords: STEM education; STEM school; distributed leadership; school administration

Citation: Wieselmann, J.R.; Roehrig, G.H.; Ring-Whalen, E.A.; Meagher, T. Becoming a STEM-Focused School District: Administrators' Roles and Experiences. *Educ. Sci.* **2021**, *11*, 805. https://doi.org/10.3390/educsci11120805

Academic Editors: Andrea Burrows and Mike Borowczak

Received: 15 October 2021
Accepted: 7 December 2021
Published: 10 December 2021

1. Introduction

Science, technology, engineering, and mathematics (STEM) education continues to receive educational emphasis in the United States and in many countries around the world. Within the United States, the *Next Generation Science Standards* (NGSS) [1] provide policy guidelines for STEM education through the inclusion of engineering practices and the promotion of the integration of mathematics and computational thinking within K-12 science learning contexts. At this time, 44 states have either adopted the NGSS or developed their own educational standards based on *A Framework for K-12 Science Education* [2], which was the foundation for NGSS development. With this widespread influence of the NGSS reaching over 70% of US students [3], it is clear that the country has shifted from the rote memorization of scientific facts toward the authentic engagement of students in STEM practices.

The President's Council of Advisors on Science and Technology pointed to STEM education as the determining factor in responding to the challenges of the 21st century, and called for the creation of STEM-focused schools [4]. A large number of STEM schools exist and continue to emerge, but there is a lack of clarity about what it means to be labeled as a STEM school. The Committee on Highly Successful Schools or Programs for K-12 STEM Education identified three different STEM school types: (1) selective STEM high schools, (2) inclusive STEM high schools, and (3) STEM-focused technical and career readiness schools [5]. In addition, some STEM schools focus on providing strong instruction in each of the separate STEM disciplines, while others focus on STEM integration, merging the disciplines. This lack of consensus extends to the conceptualization or definition of integrated STEM education [6–12], with researchers also questioning the relative emphasis placed on mathematics and technology compared to science and engineering [13–15].

Despite the range of approaches to STEM education, it is clear that school-level systems and supports are needed in order to sustain STEM education efforts [16–18]. STEM schools and districts continue to emerge, and while there is some research highlighting the critical components to be included in STEM schools [17–19], there is a need to learn more about the process of becoming a STEM school or district. In this study, we investigated a rural school district's development and expansion of its STEM education focus. In particular, we addressed the research question: How is a district-wide STEM education vision developed, enacted, and sustained by various administrative stakeholders?

2. Literature Review

A variety of STEM schools have emerged in the US, utilizing a range of admissions procedures and criteria [5]. Selective STEM schools are often highly competitive and tend to have a low enrollment of minority students [20], which is concerning given the ongoing underrepresentation of minorities and women in STEM fields [21]. In contrast, inclusive STEM schools have an explicit focus on equity, and focus specifically on serving historically underrepresented youth [18,22]. These schools operate on the premise that STEM skills and practices can be developed for all students, and that students from traditionally underrepresented groups need to experience opportunities for STEM development [23]. Non-selective admissions policies allow students who may not have experienced past success in science or mathematics to attend inclusive STEM schools, with the goal of developing their interest and ability in STEM.

There remains a need for additional research on STEM schools, but some promising results have emerged from studies of inclusive STEM schools. Comparing the achievement outcomes of students attending inclusive STEM high schools to those attending traditional high schools in Texas, Young et al. [23] found small but statistically significant effects that favored students who attended STEM schools. The outcomes included increased student attendance rates, as well as higher performance on standardized tests of reading, mathematics, and science. Using a longitudinal dataset of students attending New York City public high schools, Wiswall et al. [24] found that students attending a STEM high school outperformed those who attended schools without a STEM focus on tests of mathematics and science. However, once prior performance was accounted for, this advantage was greatly reduced.

Although the findings regarding the presence and magnitude of achievement outcomes linked to inclusive STEM high school attendance are mixed, various studies have provided evidence that the benefits of attending an inclusive STEM high school extend to interest in STEM [20,25,26], confidence in pursuing higher education [20], the completion of advanced mathematics and science coursework [23,26], and STEM career aspirations [26], with students attending inclusive STEM high schools demonstrating more favorable outcomes than their peers attending traditional high schools. Notably, two studies [24,27] found that the benefits of inclusive STEM high schools are greater for students from traditionally underrepresented groups, and that inclusive STEM schools may contribute to increased equity in STEM.

While these results are promising, the majority of the positive findings have had small effect sizes, and may not have adequately accounted for students' prior academic achievement. Research by Eisenhart et al. [28] suggested that the initial successes of STEM schools may be difficult to maintain over time. Indeed, Gnagey and Lavertu [29] found that inclusive STEM high schools were sometimes associated with negative effects on both STEM and non-STEM achievement. The researchers attributed these negative effects to a focus on problem-based, personalized learning at the cost of science and mathematics content.

The majority of studies, including those already described in this section, focus on established high school contexts and student outcomes associated with STEM school attendance. There remains a gap in the research base related to the process of becoming a STEM school or district. Within this limited research base, the most prevalent studies explore the initiation of STEM programs within a school, for example the addition of (a) after-school STEM programs [30,31], (b) robotics and makerspace curricula [32,33], and (c) STEM projects [31,34–36]. A small number of studies have systematically explored the opening of a STEM school. For example, Sikma and Osborne [37] identified tensions between top-down approaches to education and the need for teachers to redesign STEM curricula within an elementary STEM magnet school. Siegel and Giamellaro [38] used a phenomenological approach to explore how STEM was defined in a school district, particularly focusing on teachers' adoption and appropriation of "STEM", emphasizing teachers as co-designers of school innovation. In a follow-up study, Siegel and Giamellaro [39] explored the work and contributions of the non-STEM teachers in the district. The use of the engineering design process to support the implementation of STEM was central for non-STEM teachers to incorporate STEM into their instructional practices. Slavit et al. [34] explored the work of teachers during the start-up process and first year of an inclusive STEM middle school. The teachers needed more specific support to successfully develop integrated STEM projects because a vision for STEM and problem-based learning was not solidified during the first year as a STEM school. Most critical was the willingness of the teachers to work collaboratively as curriculum designers and to take risks, an attribute also noted by El Nagdi et al. [40] in their study of an emerging STEM program in an urban middle school. Finally, Rissman-Joyce and El Nagdi [41] reported on lessons learned from the initial two years of Egypt's first STEM school; the central needs were the teachers' professional development, the development of rubrics for better assessment within project-based learning environments, and ways to address the range of English language and computational skills within the student population. El Nagdi and Roehrig [42] explored the development of the first Egyptian STEM school for girls through retrospective interviews with teachers, revealing the need for ongoing professional development over multiple years to establish both the understanding and implementation of the STEM mission. This involved significant changes in beliefs and practices for teachers to transition from traditional pedagogical approaches to integrated STEM.

In addition, while inclusive STEM schools are undoubtedly doing important work, it is important to consider the development of STEM-focused missions within public school settings in which students attend neighborhood schools. These neighborhood schools, which may or may not explicitly focus on equity and inclusion, can support efforts to achieve the goal of making quality STEM education accessible to all students. The present study, with its focus on the process of developing and implementing a district-wide STEM mission from the perspective of district and school administrators, contributes new perspectives to the research base.

3. Theoretical Framework

School leaders take on a range of responsibilities, which can be categorized into four key domains: setting directions, building relationships and developing people, developing the organization to support desired practices, and improving the instructional program [43,44]. Distributed perspectives of leadership point out that these responsibilities do not reside within a single individual, but rather are dispersed for a collaborative approach [45]. This distribution of leadership roles and responsibilities can be important for sustaining change in schools [46], and may even be able to support a school's social justice agenda [47].

Distributed leadership theory draws upon distributed cognition and activity theory to emphasize the importance of the social context in learning and activity [48]. A variety of contextual factors, ranging from school histories and teacher experiences to budget and legal requirements, impact the work of school leaders [44]. School leaders take on both macro-functions and micro-tasks [48]. The macro-functions include large-scale organizational tasks, such as constructing a school vision or developing structures for teacher collaboration. Micro-tasks involve the day-to-day work of leaders, such as conducting classroom observations or engaging in Professional Learning Community meetings with teachers. These macro-functions and micro-tasks are distributed across a variety of school leaders, resulting in the need to consider leadership at the collective level [48]. The tools, artifacts, and organizational structures that surround this leadership work must also be considered [48].

Since its inception in the early 2000s, a number of empirical studies have explored the effects and impact of distributed leadership, with evidence of positive results related to both organizational conditions and student outcomes. For example, in a longitudinal post-hoc study of distributed leadership for school improvement in 197 elementary schools, Heck and Hallinger [49] found that distributed leadership was significantly related to school improvement capacity and student learning outcomes. Other studies have found distributed leadership to be linked to student achievement via teacher motivation [50], professional community [51], or by building capacity for academic improvement [52]. This study utilizes distributed leadership theory to frame our work, considering the roles and perspectives of a range of district- and school-level leaders in the process of developing and enacting the district's STEM mission across its schools.

4. Analytical Framework

With ongoing uncertainty about what it means to be a STEM school, two key studies sought to highlight the characteristics of exemplary STEM high schools, using two different strategies to distill the critical components (CCs) of effective STEM schools. LaForce et al. [17] studied 20 inclusive STEM high schools from across the US, and identified eight CCs of the schools based on school leaders' and teachers' descriptions of their school's STEM model. The eight elements include: the personalization of learning; problem-based learning; rigorous learning; career, technology, and life skills; school community and belonging; external community; staff foundations; and external factors. Notably absent in this list of CCs is any explicit connection to STEM.

Peters-Burton et al. [18] conducted a literature review to identify 10 CCs of exemplary STEM schools based on existing research. Following the subsequent data collection and inductive analysis of exemplary STEM high schools, four additional CCs were identified [19]. These 14 CCs are the basis for *CC1–CC14* in Table 1. In their case study of eight exemplary STEM high schools, Lynch et al. [19] found that while all of the components were present to some extent across the schools, different schools emphasized different components based on their missions. Given the focus of the present study on school and district leadership, the CCs identified by Peters-Burton et al. [18] and Lynch et al. [19] are well-aligned with our research question. In particular, *CC9* (flexible and autonomous administration) and *CC12* (innovative and responsive leadership) focus explicitly on school leaders. However, we also modified some of the CCs to increase their relevance to the current study. For example, the original *CC1* is focused on college preparation through a STEM-focused curriculum; given the current study's span from elementary through to high school, we removed the college preparation element from this CC (see Table 1 for operational definitions of all of the CCs).

Table 1. Critical components (CCs) adapted from [18,19,53].

High School CC	CC Operational Definition in This Study	Related Elementary School CCs
CC1. STEM-Focused Curriculum	Science, technology, engineering, and mathematics are explicitly, intentionally integrated across the curriculum.	STEM is integrated throughout school curricula School schedule includes more than required minutes of science instruction School programs are coherent and supportive of STEM School builds college awareness, college-going culture, and career awareness
CC2. Reformed Instructional Strategies and Project-Based Learning	Instructional practices are informed by research for active teaching and learning, immersing students in STEM content, processes, habits of mind, and skills. Project-based learning situated in an authentic context is encouraged.	Instructional approaches include project-based learning and other reform strategies Teaching and learning emphasize inquiry or design thinking Students participate in service learning or other community activities
CC3. Integrated, Innovative Technology Use	Technology is used to connect students with information systems, models, databases, research, and teachers.	Technology is integrated into activities of both students and teachers
CC4. STEM-Rich Informal Experiences	Students have opportunities for STEM learning outside of the formal school day.	Out-of-school programs and resources provide STEM-rich experiences
CC5. Business Partnerships	Partnerships with business and industry increase the school's capacity for STEM programming.	External partners deepen the school's STEM capacity
CC6. College and Career Readiness	Students develop an awareness of college and career options as well as the skills that will support their success in these areas. Teachers facilitate student knowledge of and interest in STEM careers.	School builds college awareness, college-going culture, and career awareness Students learn and use workplace and life skills Teachers facilitate student interest in STEM
CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff	Teachers are highly qualified and have advanced STEM pedagogical content knowledge and/or practical experience in STEM careers. Teachers have opportunities for professional development, collaboration, and interactions with STEM professionals.	Teachers are supported in STEM through collaboration, training, and resources Teachers are open to innovation and continual learning
CC8. Inclusive STEM Mission	The school provides STEM learning opportunities for all students, who are representative of the local community.	School population represents district or local community
CC9. Flexible and Autonomous Administration	The school has autonomy from the school district to address the goals of its innovative STEM program.	School administration is flexible and autonomous
CC10. Supports for Underrepresented Students	The school provides supports (tutoring, advisories, and special classes during and outside of school hours) for students to strengthen their STEM content knowledge and skills.	
CC11. Data-Driven Decision Making for Continuous Improvement	Assessment and data systems support continuous improvement in teaching strategies, student supports, professional development, and resource allocation.	Dynamic assessment systems inform instruction Staff use evidence in continuous improvement process of school model or programs

Table 1. *Cont.*

High School CC	CC Operational Definition in This Study	Related Elementary School CCs
CC12. Innovative and Responsive Leadership	School leaders are proactive and continuously address the needs of teachers, students, and the greater community through innovative solutions, open communication, and uplifting leadership. School leaders allow for teacher agency in planning and implementing instruction.	School leadership is inclusive and focused on instruction
CC13. Positive School Community and Culture of High Expectations for All	A culture of high expectations for students and staff is maintained in a school environment built on trust and respect. Students and staff feel a sense of personal, intellectual, and social-emotional safety.	Trust and respect are shared among staff and students
CC14. Agency and Choice	Students have agency and choice in their learning. Teachers have agency and choice in their teaching.	Students experience autonomy in learning
CC15. Community and Family Involvement	Families and the community have a voice in decisions and are included in the school. The school establishes and maintains a community presence.	School establishes and maintains a community presence Parents are included in classrooms and the school
CC16. Sustainability	STEM programs are designed with attention to sustainability, scalability, spread, and flexibility.	Program designs include sustainability, scale, spread, and flexibility

Since the identification of the 14 CCs deemed essential for effective inclusive STEM high schools, additional studies have explored the relevance of the CCs at different levels. For example, Crotty [16] applied the CCs to three different middle school contexts, focusing on their relationship with teacher leadership. Peters-Burton et al. [53] conducted a case study of an effective STEM elementary school to identify CCs that were characteristic of the school, resulting in 24 CCs for this school. In the comparison of the elementary and high school CCs, we identified some clear areas of overlap (see Table 1). However, there were three elementary CCs that were not fully captured in the existing set of high school CCs identified by Peters-Burton et al. [18] and Lynch et al. [19]: (a) the school establishes and maintains a community presence; (b) parents are included in classrooms and the school; and (c) the program designs include sustainability, scale, spread, and flexibility. Because of the potential importance of these elements in the present study, we added *CC15* and *CC16* to our analytical framework (see Table 1).

5. Materials and Methods

Narrative inquiry positions lived experiences as a key component of knowledge and understanding [54,55], allowing researchers and participants to collaborate as they tell and retell individual and social stories [56]. Dewey's [57] theory of experience underpins narrative inquiry because of its focus on interaction and continuity enacted in situations [56]. This focus on experience is a defining feature of narrative inquiry [58], with experience itself serving as the phenomenon of study [59].

Narrative inquiry offers a pragmatic way to frame individuals' experiences within social, cultural, and institutional narratives [58]. Personal, practical, and theoretical justifications are necessary for narrative inquiries [60], and interviews serve as the primary method [61]. The analysis of narratives involves collecting stories as data, then analyzing those stories using a paradigmatic process, resulting in a set of themes or findings that are consistent across the stories [62].

Narrative inquiry includes three "commonplaces" across studies: temporality, sociality, and place [56,59]. First, temporality refers to the timing of the events or experiences being studied. These are seen in "temporal transition" [59] (p. 479) with a past, present, and future. Experiences are informed by what has already taken place, occur in the present moment, and are also carried into the future [58]. Narrative data that include information about the temporality of events and experiences are classified as diachronic; in contrast, synchronic data are categorical responses in the present with no reference to development over time [62]. Second, sociality refers to concern for both personal conditions, such as feelings, hopes, and morals, and social conditions, such as the environment and surrounding factors [59]. This dual focus means that narrative inquiry does not focus solely on a person's thoughts and feelings or, conversely, on the social conditions; rather, it is the integration of both conditions that defines narrative inquiry. The relationship between participant and inquirer is another element of the sociality commonplace [59]. Third, place refers to the boundaries of where the experience takes place, which may include a sequence of places [59].

The present study is fueled by the researchers' personal interest in the development of STEM-focused school districts, the practical need for the understanding of how the layered elements of the school district led to a STEM vision over time, and the need for theorizing and knowledge centered on the development of a STEM-focused district. We conducted interviews with the goal of understanding the experience of a school district developing a focus on STEM instruction. We considered multiple individual narratives and how they were woven together as a collective narrative of the school district in which these individuals worked.

The present study attended to the three commonplaces of narrative inquiry by focusing on the temporal aspects of the development of a STEM-focused school district. We considered what happened and when, with careful attention to the precursors and the events that followed. We considered the broad social context of district policies and decisions, as well as individual administrators' personal responses to the social conditions. Finally, our study was bounded in place by the school and administrative buildings within the district. The specific places changed across time as the STEM mission expanded across the district, and our interviews were also conducted within these district places.

5.1. District Context

This study took place in a rural school district in the Midwest United States. The district serves approximately 5000 students, and is composed of four elementary schools, one middle school (previously an intermediate school that housed sixth grade and a junior high school that housed grades 7–8), one high school, and alternative learning centers that serve students whose needs are best met outside of the traditional school setting [63]. Approximately 73% of the students are White, 15% are Latinx, 9% are Black, 2% are multiracial, and 1% are Asian. Roughly 10% of the students are English Learners, and 13% of the students receive a free or reduced-price lunch. Approximately 16% of the students have an Individualized Education Plan.

5.2. Participants

This study included 11 participants, all of whom had some level of administrative responsibility related to the district's STEM mission. A summary of the participants' positions in the district at the time the interviews took place and their associated pseudonyms can be found in Table 2. It should be noted that the fourth author of this study was also a participant, being the district STEM coordinator. Our relationship was developed through graduate studies and ongoing collaboration related to this and other projects. This long-standing relationship led to connections with others in the district.

Table 2. Study participants.

Position at Time of Interviews		Pseudonym
Superintendent		Mike
Director of Teaching and Learning		Lisa
STEM Coordinator		John
Elementary School Principal		
	Elementary A	Daniel
	Elementary B	Jennifer
	Elementary C	Heather
	Elementary D	Kelly
Middle School Principal		Laura
Former Administrator		
	Former Principal of the Intermediate School	Eric
	Former Principal of Elementary A	David
School Board Member		Tammy

5.3. Data Collection and Analysis

Because of the fourth author's position as district STEM coordinator and his ongoing collaboration with the other authors throughout the time of the study, the data collection was ongoing, and included both formal and informal observations. However, the primary data source for this study was in-depth interviews conducted with each of the participants. These interviews used a semi-structured interview protocol with items prepared for each participant based on their role in the school district in order to allow for consistency across the interviews while also providing the opportunity for follow-up questions tailored to each individual [64]. The key topics of the interview protocol included the individual's history in coming into their role; the mission and vision of the school or district, and how STEM fits into that mission or vision; the STEM opportunities available to students and teachers; community and business connections; teacher preparation and professional development; and the response to the STEM initiative from teachers, students, parents, and community members. These interviews were conducted over the course of several years.

Through consultation with John, the district STEM coordinator, we created a timeline of key events in the district's STEM mission development and implementation, such as the adoption of the STEM mission by additional schools. This timeline was used to frame the narrative inquiry. With the timeline in place, the interviews were transcribed and deductively coded in Google Docs based on the CCs in our analytical framework. We also wrote detailed memos about the big ideas from each interview. Using the coding and memos, we mapped key critical components to the different phases of development. This allowed us to integrate the narrative shown in the timeline with the critical components framework. We utilized constant comparative analysis [65] and continually returned to the interview transcripts and memos, extracting quotes that supported or refuted the CCs deemed most critical in each phase. We also referred to meeting minutes from the school board for additional details related to the key decisions.

6. Results

In our analysis of the interview data, we identified key CCs that were emphasized at different points in the district's STEM timeline. In this section, we use a chronological narrative to describe the events happening in the school district, as well as the CCs that featured most prominently in each time period. The key events in the district's STEM timeline can be seen in Figure 1. Wherever possible, we include multiple individuals' perspectives related to the CCs in each time period; where space limitations make this impossible, precedence was given to the individual who expressed a shared idea most clearly and concisely.

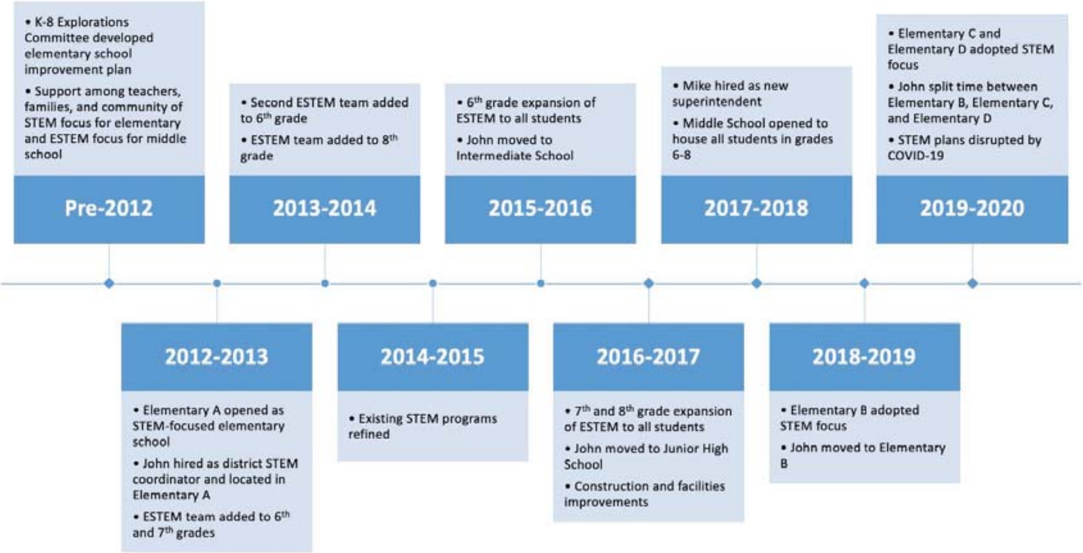


Figure 1. District STEM timeline.

6.1. Pre-2012

In the years leading up to the district's adoption of a STEM mission, the schools in the district faced a number of challenges. With concerns about accountability related to the No Child Left Behind Act, the failure of two elementary schools to make adequate yearly progress (AYP) on standardized tests left them at risk of being taken over by the state department of education. John, a veteran science teacher in the district and the STEM coordinator starting in 2012, described the following:

> [Elementary A] and [Elementary D] were on the verge of being taken over by the state because their students were not making AYP [adequate yearly progress]. [Elementary A] in particular had been suffering from white flight from the school. The atmosphere was toxic. I mean . . . teachers had the highest request to leave [Elementary A] to go to other schools. That was happening during like 2009, 2010, 2011.

With the need to develop a school improvement plan, the superintendent at the time put together a K–8 Explorations Committee to explore possibilities for the improvement of the elementary schools. Demonstrating *CC12. Innovative and Responsive Leadership*, the superintendent sought input from other administrators and teachers to meet the needs of the schools through innovative solutions. David, who was the Principal of Elementary A at the time, explained that "It got to the point where they put together a task force that consisted of elementary teachers and elementary principals. There were three principals that really led the charge on this."

This committee ultimately recommended making the four elementary schools into choice schools with different foci: STEM, environmental education, project-based learning, and the traditional approach. The committee solicited feedback on the school options from teachers. John recalled:

> When the K-8 Explorations Committee brought these ideas to the schools themselves, teachers all went, 'No!' except [Elementary A]. [Elementary A] teachers said, 'We want to do STEM!' And so, then the school district said, 'OK we've got one school, we have one idea . . . ' [Elementary D] decided to stay on a more traditional instructional pathway, with the district investing in more faculty support

> with educational assistants, paraprofessionals, Response to Intervention faculty, and a special education teacher to focus efforts on the group of students with the greatest need for additional support. Experimenting with a single school out of four was safer than trying STEM with two schools.

David also described this enthusiasm for the STEM-focused elementary school among Elementary A teachers:

> Our staff came back overwhelmingly, they wanted to do STEM . . . Out of all the schools that were surveyed, our school was the only one that said we're willing to change. We would have never been as successful as we were, I think, if we wouldn't have had the buy-in from the staff.

Demonstrating *CC15. Community and Family Involvement*, the teacher surveys were followed up by surveys of the parents and community. John explained, "And so then they put the ideas out to the community members and to the parents and the neighborhood area. And it was overwhelming. It was like 85 percent of the community members said, 'We want [Elementary A] to be a STEM school.'"

With the idea of the Elementary A STEM School receiving support from the teachers, parents, and community, the district leaders started to perform research to explore existing STEM schools and create their vision for Elementary A. David recalled:

> We started doing some research . . . We also did tours of other buildings around the metro. What we found is we didn't want to be like them because we didn't want to teach science, technology . . . engineering, and math. We didn't want to just teach those subjects. I did not want to have STEM be a stand-alone class. I didn't want a STEM teacher. We wanted STEM to be embedded throughout the entire curriculum. We kind of joked around. I said, "We're going to STEM-ify our curriculum."

While the environmental education and project-based learning approaches were not taken up by the elementary teams, the environmental STEM (ESTEM) focus was of interest to the sixth-grade team at the Intermediate School, largely given its proximity to a 27-acre natural area. This decision resulted in an ESTEM focus also being brought into the middle school for the purpose of continuity. John explained:

> [The Intermediate School] had a nature area that ran out the back door. So, when the teachers were asked, they wanted to do environmental STEM. Since [the Intermediate School] was already doing it, we viewed it as a natural extension to run the ESTEM program all the way through middle school.

This district vision for STEM across all of the disciplines continued to gain momentum and was further refined in the ensuing years.

6.2. Academic Year 2012–2013

The 2012–2013 academic year marked a major transition in the district's implementation of its STEM mission. Elementary A opened its doors as a STEM-focused elementary school. In addition, one ESTEM "house" or team (out of four teams at each grade level) was added to the sixth grade and seventh grade. *CC12. Innovative and Responsive Leadership* continued to be critical during this transition as the infrastructure was put in place (e.g., installing a garden in the Elementary A courtyard) and hiring decisions were made. One key decision was hiring John as the STEM coordinator, and locating him in Elementary A to respond to teachers' needs and provide ongoing support. David recalled this decision, sharing, "When we became STEM, I said, 'We need a STEM coordinator. Not a STEM teacher. We need a coordinator that's going to instruct our teachers how to instruct and help them.' John was a guy that I had in mind right from the start because I knew he's phenomenal."

Another key decision was pairing STEM and literacy coaching at Elementary A. David described:

> We had those two people [STEM and literacy coaches] who are instructing our teachers how to teach together. I allowed them then to develop our program at [Elementary A]; how are we going to not let go of our reading to teach all this new STEM stuff and how are we going to continue teaching the STEM techniques in our reading, in our math, in everything else? I think the biggest thing that we did is we combined those two. A lot of times you'll see in other buildings, you'll see they're separate. They're in totally separate areas. That was huge.

This decision also supported John as a high school science teacher shifting to a position in an elementary school. John recalled:

> When we started, [an elementary teacher] was asked to be an instructional coach to team with me because I was a secondary teacher, and her role was to work with me in determining how to implement STEM in K-5. We worked really well together, and once they [district administrators] started seeing how well this was working and how teachers were benefiting from instructional coaching, they expanded the instructional coaches.

In a further demonstration of *CC12. Innovative and Responsive Leadership*, some level of teacher agency was maintained despite the teachers being asked to shift their instructional practices. The school and district leaders allowed the teachers to adopt STEM instruction at different paces. They also provided them with the option of moving to another school or team if they did not want to participate in the STEM mission at all. John recalled the experiences of an Elementary A teacher who considered moving to another school:

> She was terrified of the idea that [Elementary A] was going to be a STEM school. She thought she was now going to have to be a science teacher but decided that she wanted to do something different and was trusting that it would be OK. By the end of the second year, she came to me and to David ... and she said she wanted to thank us because she said, "I was terrified. I was thinking about transferring to [Elementary C]. I wasn't sure if this was going to be it. Now I can't imagine teaching any other way." Many people started out very scared and uncertain, but with support, they changed.

In preparation for the implementation of the STEM mission, there was a newfound focus on *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff*. The district held a multi-day professional development event for teachers over the summer prior to the opening of the Elementary A STEM school, and also provided substitute teachers during each trimester of the school year so that the grade-level faculty could engage in STEM unit and lesson planning. Professional development opportunities were provided to all of the teachers, not just those responsible for teaching the STEM disciplines.

Despite these trainings, there was some resistance among the Elementary A teachers. David explained, "We had some growing pains when we decided we were going to do this. Because we had some teachers that were just loving it and others that were scared to death because they were going to have to change." Similarly, Eric, the principal of the Intermediate School, which housed the sixth-grade STEM team, described teachers' resistance to change:

> Some of them [teachers] took it very personally, they're like, "I've been teaching for 22 years. How dare you come in and tell me that I'm not doing it right?" And I'm like, "No, no, no, it's not a matter of right and wrong. It's a matter of trying something." And he's like, "No I've been doing this for 22 years. You don't seem to understand. I'm highly respected."

These shifts in teaching reflected an emphasis on *CC2. Reformed Instructional Strategies and Project-Based Learning*. While some teachers fully embraced STEM instruction, others made more limited changes. For example, these teachers complied with the STEM initiative by participating in cross-disciplinary projects that included all of the teachers at that grade level. However, when their students were not participating in a specific STEM project, these teachers would rely on traditional instruction and utilized lessons they had taught in previous years. These initial collaborative STEM projects served as starting points for a way to develop a shared understanding and a shared language around STEM teaching and learning. Eric explained:

> The approach we took, it's really about the teaching style. It's not a STEM class or a STEM project, or it's not like you all of a sudden shift gears, and now we're going to do our STEM project. It's about, you know, maybe switching your mode of teaching into one where the students do more journaling, more observations, more explorations, realizing there's a growth mindset . . . some teachers, you know they've had their worksheets laid out for 16 years, and "I've gotta do this worksheet at this time. And I've gotta mark all the right and wrong answers" and that sort of thing. And they really struggle to get out of it. So, they would implement some projects that were cross-disciplinary to make sure that everyone was kind of using the same language to do that.

While the vision of STEM as a cross-disciplinary pedagogy was consistent across the administrators, there was less clarity around *CC8. Inclusive STEM Mission*. The very nature of only including some students and teachers in ESTEM houses in the Intermediate School was divisive. Eric recalled:

> It ripped the building apart, even as far as morale and everything else, because . . . everyone applied for STEM, and then some teachers were called STEM teachers and other teachers were not called STEM teachers, so it was, "Oh, you're better than us, we're not as good as you." It's the haves and have-nots. The people who were accepted into STEM received a lot of paid training during the summer, and they also received unbelievable amounts of technology.

John explained that the perception of inequity among the teachers extended across school boundaries as well:

> The other schools saw the amount of professional development the STEM teachers were getting, and that also brought along some jealousy. Some have and have-not feels . . . Teachers at the other schools first saw it as, "I'm glad it's not us." Now [in 2018] they are saying, "Why can't it be us?"

Reflecting on these issues with the egalitarian nature of schools, John recognized tensions in district practices and messaging that may have contributed to these perceptions of inequity. District-level leaders believed that all schools should implement the district curriculum to provide similar instruction across sites. With this message, the freedom for certain teachers to deviate from the district curriculum could be perceived as inequitable. However, the school-level leaders were also afforded some level of ownership of their schools to create unique school cultures, but it is possible that this autonomy was overlooked by teachers if it was not further distributed to them.

In addition to these issues with inclusivity among the teachers, Eric also saw problems in the ways in which the students were viewed and treated:

> I felt like when I came into the building, just equity-wise, we were writing kids off really fast. Teachers would give me a list of kids they planned to leave behind on an upcoming field trip, not because of a specific incident, but because they had been a pain for a while. And I was like, "No, no, no. We're not going to function that way. Every student in this building is coming along. We had a lot of those things going on, where it was like students were being held back or pushed aside or divvied up.

6.3. Academic Year 2013–2014

In the second year of the STEM program implementation, the STEM mission continued to expand to include additional teachers and students. A second ESTEM team was added to the sixth grade at the Intermediate School, and an ESTEM team was also added to the eighth grade. *CC8. Inclusive STEM Mission* continued to be critical, now in relation to the demand for places in the STEM sections of grades 6–8. Tammy was on the district's school board at the time, and explained:

> Once the one building was identified as a STEM school, we were doing some boundary changes ... There was discussion of an open enrollment phase and so on. It was clear that the STEM school was a big draw, so it continued to get more and more attention. I would also say it's interesting because from my perspective, I'm not sure that those people who sought it really understood what they were seeking. You know what I mean? I mean it had a good reputation, you know you hear about it [STEM] in national and state news, I mean the issue is out there. So, I think that kind of bought into that, not always sure that they fully understood what it was they were buying into.

With this high demand for STEM education, the district leaders had to make difficult decisions about how to allocate the limited number of STEM positions. The students who attended Elementary A were guaranteed a position in one of the two Intermediate School ESTEM houses, but that left Eric to decide how to fill the remaining positions:

> All of a sudden, I had far more applicants for STEM than I had here. We knew it was coming, but yet we weren't responding. And so, we stayed two [STEM] houses and two [non-STEM] houses. So, then we went into a lottery system. And again, if your parent is feeling like their child is not getting an equal opportunity for an education, they're not going to be happy. So, I had a lot of office visits before that year started with parents crying, parents yelling, and parents screaming, "Why are you denying my child this opportunity that will lead to them being a successful engineer?" Or you would hear people say, "My child is one of the smart ones. They belong in STEM." And I would say, "You do realize that STEM ... applies to all kids. It's not for the gifted and talented, it's not for the disengaged, it's for all kids."

Seeing this demand for STEM instruction and realizing that additional resources would be needed to expand the reach of STEM education, John began to focus on *CC5. Business Partnerships*. These connections were largely structured to provide funding for supplies and professional development to teachers, rather than providing students which access to industry approaches or opportunities. John recalled one of his first meetings with a local company interested in supporting the STEM mission:

> They approached the school district and said, "We have a community grant fund that we want to support STEM education." And so, the district administrators were going to go to that meeting. My principal said, "Well you should probably come, too." And we went to the [company] office and were talking to the director of the community resource grant fund ... and she said, "What are you envisioning for STEM?" One after another, people named stuff. "We want a FAB Lab. We want 3-D printers. We want robots. We want stuff." And I'm listening to this and thinking, "Nobody gets it." If you just buy stuff and throw it at teachers, it'll sit there. They need to know how to do it. So, then I asked if any of these funds could go towards professional development, and she said, "That's the primary thing we want to do! We really want to work with teachers!"

This meeting resulted in a grant of approximately $35,000 in each of the ensuing years to pay for teachers to complete a graduate STEM certificate program from a nearby university. Similar partnerships provided funding for professional development related to STEM and arts integration, as well as the implementation of STEM notebooks. By pursuing external funding, John continued to emphasize *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff*.

6.4. Academic Year 2014–2015

After two years of major transitions, the 2014–2015 academic year provided a period to refine existing STEM programs, continue teacher professional development, and prepare for more transitions in the following year. John continued to provide support focused on STEM instructional strategies for teachers at Elementary A.

In addition, *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff* was evidenced in the work being performed by the Elementary A art teacher. She received a grant to focus on arts integration, and in addition to professional development, she collaborated with teachers to bring arts into their STEM instruction. This effort was ultimately recognized by the National Endowment for the Arts and the Obama administration in 2015.

6.5. Academic Year 2015–2016

In the fourth year of the STEM program implementation, the seventh and eighth grades maintained the same number of STEM houses. However, the Intermediate School expanded its STEM focus to include all four of the sixth-grade teams, becoming an ESTEM school. With this shift, John moved from Elementary A to the Intermediate School to provide on-site support for teachers, continuing to emphasize *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff*. Eric recalled John's critical role in supporting teachers:

> [John] was tremendous . . . because he has a reputation for not being judgmental. He doesn't come in and say, "You're doing it wrong, do it this way, do it that way." He just comes in, and sometimes he'll model a lesson. He's comfortable doing that on many different levels. He'll talk to teachers outside class, and he'll sit while they do it [teach STEM]. Sometimes he'll come in and teach and say, "Let me show you what I mean by this." So, he's very gifted that way because the teachers didn't find him threatening at all.

This focus on *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff* also included collaboration among teachers. Eric sought opportunities for teachers who were new to ESTEM to learn from those who had more experience. The teachers also continued to work together through Professional Learning Communities to establish a shared understanding of STEM instruction.

With David moving to a new position in the district, Daniel started as the principal of Elementary A. He had worked in the district since 2005, first as an elementary teacher at Elementary A and later as a Teaching and Learning Coordinator. Because of this role, he already had experience working with principals and teachers within the district, as well as an understanding of the district dynamics. He also received his STEM certification with the first cohort of teachers from Elementary A. He described the shared visioning process as he stepped into the role of Elementary A's principal:

> When I started in this position, it was all over the board with what was happening. So, it was a STEM school, but I would have a conversation with someone who would make a comment that STEM was the curriculum, and then across the hall, their teaching partner would say, "It's not a curriculum." It was completely opposite conversations, so we did some work my first year to identify our elevator speech. When we see people in the community, what do we believe as a school? And from that, we came up with growth mindset, higher-level questioning and thinking, and then real-world integration.

These conversations again highlighted *CC2. Reformed Instructional Strategies and Project-Based Learning*, and solidified the earlier emphasis on STEM as a pedagogical approach rather than a curriculum.

6.6. Academic Year 2016–2017

In the fifth year of the district's STEM program implementation, the STEM mission again expanded. Rather than having a single ESTEM-focused team for grades 7 and 8, all of the seventh and eighth grade teams began to focus on ESTEM. With this shift, John transitioned to the Junior High School location to provide support for these teachers. As the teachers became more comfortable with STEM, they focused on *CC2. Reformed Instructional Strategies and Project-Based Learning*, developing new projects for their students. For example, Intermediate School sixth-graders participated in engineering days twice in the school year, and had numerous outdoor learning days in the nature area. The teachers designed a "cardboard arcade" event that challenged the students to design a functional arcade game using cardboard and limited materials, collecting and analyzing data related to the odds of winning the game.

With an approved tax levy for building construction, there was also a major focus on district facilities. John recalled:

> I had been meeting with architects a lot to help design classrooms, science labs, and things like that. The goal was to open the new middle school in the fall of 2017, so they were doing a lot of remodeling. [Elementary A] was going to move to the old [Intermediate School] building, [Elementary B] was going to move into [Elementary A's] old site, and then [Elementary C] and [Elementary D] were both getting additions. This was all happening in a matter of about eight to nine months, so there wasn't a lot of extra curriculum development happening. It was really focused on creating 21st century learning facilities.

6.7. Academic Year 2017–2018

Two key transitions occurred in the sixth year of the district's STEM program's implementation. First, Mike was hired as the district's new superintendent. Second, building on the transitions from the previous years, grade 6 (previously housed in the Intermediate School) moved to the newly remodeled middle school, creating a single school building for grades 6–8. The expansion of the school included a bigger cafeteria, a new flexible performance space, and a focus on collaboration through central gathering areas and breakout rooms for small groups. In the new physical environment, the school was deemed an ESTEM school, with all teams of all grade levels focusing on STEM. Elementary A also shifted physical location, moving into the remodeled building that previously housed the Intermediate School. With this move, the district also shifted its focus from STEM to science, technology, engineering, arts, and mathematics (STEAM), based largely on the Elementary A art teacher's extensive arts-integration efforts starting in the 2014–2015 academic year.

With this reorganization, some changes were made to the school-level leadership. Eric, previously the principal of the sixth-graders at the Intermediate School, became the principal of the Alternative Learning Center. Laura, who was previously the principal at Elementary D, was brought on as the principal of the middle school. John also moved locations to the middle school to support those teachers in STEM instruction. He recalled Laura's leadership in relation to *CC12. Innovative and Responsive Leadership*. John said, "[Laura] was beloved at [Elementary D] and is an amazing teacher. And that was a big decision to bring [Laura] to the middle school as they went through this transition. [Laura] is really supportive of her teachers, and I think that reflects how people teach kids."

In her new leadership position, Laura emphasized *CC12. Innovative and Responsive Leadership* by seeking teacher input, as well as *CC14. Agency and Choice* by soliciting input from students and parents about what elective courses to offer. She described:

> When we started, we asked parents, "What do you want?" And we asked kids, "What do you want?" We asked teachers, "What would you want to teach?" And then once we came together with a list, we did a survey of the kids . . . We have 40 electives that kids had the chance to choose from this year, which is crazy at the middle school level.

Also attending to the needs and wants of students, the elementary schools started makerspace programs. Heather, the principal of Elementary C, explained her school's approach to the makerspace:

> We added a makerspace, and I have two teachers that really took that on and ran it. One day after school is how they started, and kids signed up and came. So, the kids were thrilled with it, and then we brought the kids into a staff meeting so they could share with the teachers how to use all the tools. And that was really a fun staff meeting. And so, then the teachers have been dabbling in that.

Kelly, the principal of Elementary D, described a different approach to the structuring of a makerspace and the utilization of educational assistants (EAs) to guide students:

> I introduced a makerspace this year here . . . and the students love it. That engagement and problem-solving and collaboration that they're experiencing has been really beneficial . . . I have educational assistants that help supervise it. And we come together and we try to align some of the activities with what's in the science curriculum or what they might be learning in math so it can be reinforced but also give them a different learning experience.

Laura utilized a media-focused EA to bring makerspace opportunities into the middle school, and Jennifer, the principal of Elementary B, also utilized EAs for the makerspace:

> We have EA support in there to help them, and they work with John on some creative ideas. But there's everything in there. Simple things like Legos, and Ozobots, and engineering tile. I mean there is just all kinds of manipulatives in there. And he [John] helped us . . . we didn't have this the first half of the year, but then we added a makerspace journal the second half of the year. So, they document and keep track of some of their findings . . . If you ask kids, they'll say that's a favorite time of the day.

In a third approach, Daniel created a makerspace cart that was mobile and could be easily brought into different classrooms. With these three different approaches, all four elementary schools emphasized *CC3. Integrated, Innovative Technology Use*. Even Elementary B, Elementary C, and Elementary D, which did not have formal STEM designations at this point, responded to the demand for STEM instruction and provided this opportunity for students to begin engaging in design.

Notably, John highlighted the importance of *CC8. Inclusive STEM Mission* in the use of the makerspace:

> This was a sticky issue because some people wanted to limit the enrollment in a makerspace club, and the kids had to have certain grades and certain attendance and things. And I said, "You know, honestly, if you want kids working with Ozobots, it's your special ed. kids and your kids that aren't participating in school well who probably would benefit most. Your gifted and talented kids are going to be gifted and talented anyway, but if you want to engage kids who are struggling, this may be one way." At [Elementary A], we believe STEM is good for every kid and all kids.

In his first year as superintendent, Mike also brought increased attention to *CC8. Inclusive STEM Mission*. Tammy recalled:

> Under his leadership, I think the conversation is moving forward, and we're recognizing, first of all, we've just recently redone our mission to really focus on meeting the needs of every learner. So, we look at STEM education and we say, "Well, if STEM education is great for this building and it's good enough for that other building, then why isn't it in every building?" Because we ought not be having kids kind of shop around town, thinking they're going to get a different education because that's not what public school ought to be.

Heather similarly described Mike's role in the expansion of the STEM mission to include all elementary schools:

> [Mike] came on board this year and supported that idea of moving schools to STEM, and really looking at what are the characteristics of a STEM school and

> sitting back and going, "Why wouldn't we want that for all our kids?" We want students to be engaged. We want them using science, technology, and engineering . . . And we want them being to be able to question and to be able to collaborate and design and problem solve, all of those things that are part of STEM. So pretty soon it was, "Let's all try to make this happen for all the kids . . . because pretty soon the equity is just going to be really tipped."

Further highlighting equity in student learning opportunities, Lisa, the district's Director of Teaching and Learning, said, "We believe that your address should not dictate the education you get in our district." Laura brought this equity focus to her work at the middle school. She said that "Equity work is high on our list as well. We're fairly diverse, but I think we do a lot of things that are probably a disservice or . . . unintentional disservice, but things that we could definitely do to be more of a service."

In addition to thinking about equity in relation to student opportunities, Jennifer considered equity and inclusivity among the teaching staff. She said:

> Well, we have a [school] mission statement that is empowering leaders for life . . . how do we empower everybody, not just the kids, it's the adults that work here, too. How do we empower absolutely every individual for life? All four elementary schools need to be doing this [STEM] so we don't have any haves and have-nots. We're all in it together. Because I think then the power of it will be tremendously different. The feel of it in our community will be tremendously different.

6.8. Academic Year 2018–2019

The 2018–2019 academic year marked the district's seventh year of implementing STEM programs. The STEM mission expanded to include Elementary B, which coincided with John's move to that school to provide support for STEM instruction. With the second elementary school adopting the STEM mission, *CC9. Flexible and Autonomous Administration* received new emphasis. As the principal of Elementary B, Jennifer described working as a school staff to develop their own mission and vision collectively:

> Even when the board came to us and talked to us about becoming STEM, they were like, "You know, you won't be like [Elementary A]. And we're not asking you to be like [Elementary A]. We're asking you to navigate your path and figure out what works for you." And obviously there are certain pillars of the [STEM] program that we all will have that are important to our district, but what does it look like in-house here? It may be a little bit different than other buildings. So, we're ready for the adventure!

The district-level administration provided autonomy to each school to determine the ways in which their STEM focus would be enacted. John reiterated the importance of this autonomy, stating that "We don't want the teachers at [Elementary B] or [Elementary C] or [Elementary D] to feel like this is the [Elementary A] STEM that they now have to do. We want to build a shared identity." Heather also discussed the importance of this flexibility:

> I think our current superintendent gives us a lot of autonomy. I think he wants things [to be] equitable, but it doesn't have to be the same. My building here has much different needs than the other buildings in town, like we don't have a large EL population, so things look a little different. So, I think he is certainly looking for us to make it our own but yet make sure that we're moving together as a team.

Although there was some level of autonomy granted to each school site, there was also a need for some level of consistency in STEM across the grades and buildings. While discussing the approach to STEM instruction, John said, "We've got to make sure that that's pretty consistent across grade levels." Tammy also explained:

> Just based on what I know today, I would say it's intended that it [STEM instruction] would be fairly similar [across schools]. Clearly the learning objectives in

> each of the buildings are the same. We know teachers are different and the way they approach those objectives are different. But the way they use the STEM method, I would expect it would be similar. I don't know why it wouldn't.

As the second elementary school was brought more fully into the STEM mission, *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff* was again emphasized. As in previous years, the teachers received numerous professional development opportunities over the summer and during the school year, some of which were funded through industry and business partnerships. John also continued to be a key asset in preparing and supporting the district's teachers, but with more schools implementing STEM instruction, there was some concern about how a single STEM coordinator could support teachers at multiple sites. Thinking about her schools' transition to a STEM focus in the following year, Heather described:

> He [John] was tied to [Elementary A] the first few years, and he was on-site at [Elementary A]. So, he was really working with teachers helping them design lessons . . . he was the expert on staff, and now he's been spending a lot of time at the middle school and at [Elementary B] as they roll out . . . but I don't know how that's going to roll out, that he can support all of the schools. So, I think that's a piece of it, is how do we support each school? We are bringing on instructional coaches at each elementary building, and so that is going to be one of our vehicles to help teachers.

The instructional coaches continued to provide a unique opportunity for support in both literacy and STEM instruction. Lisa, the Director of Teaching and Learning, stated that "We always have to be looking at literacy." John further explained the role of the instructional coaches and how they were utilized as STEM teaching resources. He shared:

> They [coaches] are primarily literacy, but what's interesting is I've got them both in the STEM cohort, so they are now seeing school beyond reading and writing . . . Literacy doesn't have to be just straight language arts. It can be technical literacy and scientific literacy and mathematical-inspired literacy.

With several years of STEM experience, the teachers at Elementary A also had expertise to share both within and beyond their building. Within Elementary A, the teachers collaborated to integrate STEM instructional strategies into their curriculum. Heather, the principal of Elementary C, recognized the value of Elementary A teachers. She said, "It would be awesome if we could tap into [Elementary A] staff for that and get them teaming up with our grade level teams." Teachers at Elementary B took initiative in seeking out an opportunity to meet with Elementary A teachers to collaborate. Jennifer, the Elementary B principal, recalled, "I have teams that have reached out to [Elementary A] grade level teams. We did a light and sound unit in third grade, so my third-grade team reached out to theirs and said, 'What have you done? And how did it work?' And so, they implemented some of that."

In general, the emphasis on *CC12. Innovative and Responsive Leadership* was maintained. For example, Daniel sought teacher input in renewing Elementary A's vision, asking, "What are our priorities moving forward? I'm going to be getting input from people on where should [Elementary A] be in five years? Where should we be in 10 years?" John further explained that teachers need to feel empowered through the STEM mission:

> Fundamentally, in order to make the STEM program successful, teachers and administrators need to see the benefit for kids. The community sees the benefits for kids because they hear it from their own children. But then the other key element is empowering faculty and working with them as they shift their instruction and also feel empowered to take on leadership.

However, in a counterexample of *CC12. Innovative and Responsive Leadership*, the district administration made a decision to adopt a new literacy curriculum that required a high fidelity of implementation, which teachers struggled to align with STEM instruction. John described:

> Since we STEM-ify, we take our literacy and match it with our science and with our math, et cetera . . . and teachers were just expected to pick it up and run and fit it into their STEM curriculum, but it wasn't a perfect match... And so that in particular hit the [Elementary A] teachers hardest because one thing is that we've had the permission to experiment with our instruction.

In this seventh year of STEM implementation, John continued to maintain relationships with key industry partners, but he also recognized the need to broaden the application of *CC5. Business Partnerships*. He explained that:

> One of the things they [teachers] felt weakest about was . . . Many of them said, "I don't feel comfortable trying to make connections between STEM and careers." And that's a new initiative this year. In particular, our school district wants to be more college and career ready, so I'm hoping to see that our teachers are trying to more explicitly say, "This is what it would be like in a STEM career" or "These are the kind of things you should study if you want to go into being an engineer or a scientist or if you want to do work in a company that builds computers or something." So, kids can start envisioning these jobs in the future.

6.9. Academic Year 2019–2020

As the district entered its eighth year of STEM program implementation, the final two elementary schools (Elementary C and Elementary D) formally became STEM schools, with John splitting his time between these two schools and Elementary B. In the summer of 2019, Elementary C and Elementary D teachers and principals participated in a five-day professional development event to prepare them for STEM instruction in the upcoming school year. Although this was a positive learning experience, John described some challenges in the expansion of the STEM mission to the final two elementary schools:

> I think part of the challenge was, when one school gets to be the focus, they feel a lot of pride. When it's two schools, it's like, "Well, I guess we get to finally get there." And then there was a significant number of staff that weren't available, so I think we were only able to train about 60 to 70% of the staff at each school.

Combined with principals feeling tension between STEM and other initiatives focused on literacy and mathematics, there were some barriers to STEM implementation. Despite these challenges, the teachers at both Elementary C and Elementary D began STEM instruction. However, this was disrupted because of the onset of COVID-19 in early 2020.

With STEM reaching all of the elementary and middle school students in this school year, the district continued to plan for the expansion of the STEM mission to the high school, connecting to *CC6. College and Career Readiness*. Part of this process included the approval of a bonding bill, and a $104 million bond was approved by voters so that the district could build a new high school. Mike described the design of the high school, saying that it would "be built specifically to help prepare our learners for their next step, which includes a lot more areas that will be career-oriented, so industrial technology, engineering areas."

The district administrators agreed that high school students needed some type of STEM instruction, particularly given the student demand for ongoing STEM opportunities. Laura explained, "Our eighth-graders that left here last year were so disappointed when they went to the high school because as ninth-graders, it's so structured. They don't have many elective choices." However, STEM at the high school level will look different than it does at the elementary and middle school levels. Lisa explained, "At the high school level, we're looking at career pathways." John described the possibilities for the high school, saying, "The plan is to have career-focused academies, including things like health sciences. I think it would be good if they had an academy that was labeled as STEM-focused because a lot of kids are familiar with that language from elementary and middle school." Again, because of COVID-19, the plans for the high school were put on pause.

7. Discussion

In the exploration of this school district's development and expansion of a STEM mission, the CCs identified by previous researchers [18,19,53] received different levels of emphasis at different times across the nearly decade-long narrative described here. *CC12. Innovative and Responsive Leadership* was frequently discussed as being central to the STEM mission in the district. The entire focus on STEM education was in response to community, parent, and teacher demands, and the district leaders adopted a vision for STEM that also allowed for responsiveness to teachers' needs. District and school administrators attended to both macro-and micro-leadership tasks, and distributed these tasks among individuals [48], resulting in structures and processes that involved teachers as leaders in the STEM mission. The teachers were allowed to take up the STEM mission at their own pace, and in some cases, could even elect to transfer to another school if they did not want to adopt the STEM focus. As the STEM mission expanded to include new schools, the principals experienced agency in the determination of the way in which their STEM focus would be enacted. They were not expected to adopt the same approach as other schools in the district, further connecting to *CC9. Flexible and Autonomous Administration.*

Across all of the participants, STEM was viewed as a pedagogical approach that could be implemented across disciplines. It was not connected to a specific curriculum, and instead focused on fostering student engagement, developing 21st century skills, and developing a growth mindset. Defining STEM in this way had several implications for the district and leadership decisions. There was less need to invest in an expensive curriculum and equipment, and instead a focus on building teachers' professional capacity for the implementation of STEM instructional strategies. This is evidenced by the rare discussion of *CC1. STEM-Focused Curriculum* in the interviews. Although this may seem alarming at first glance, given the district's STEM focus, STEM was adopted into the existing curriculum as teachers made use of STEM instructional strategies (*CC2. Reformed Instructional Strategies and Project-Based Learning*), which were more prevalent in the interviews. Both David and John referred to the idea of "STEMifying" the existing curriculum by making it more aligned to reformed instructional strategies. This is consistent with LaForce et al.'s [17] findings that STEM school leaders view STEM as being grounded in instructional practices, rather than being specific to disciplinary subjects. Leadership was distributed to teachers, who were responsible for collaboratively developing STEM lessons and units, and the district administrators both trusted and expected quality STEM instruction from teachers. While it was not often explicitly discussed, *CC13. Positive School Community and Culture of High Expectations for All* was implied in relation to the type of work that was expected of teachers and their students. School and district leaders saw STEM instructional strategies as being synonymous with high expectations, such as the use of higher-order questioning and the real-world applications they associated with STEM instruction. They also pointed to the belief that all students should receive rigorous STEM instruction, speaking to the belief that these high expectations should extend to all students. A positive school community was implicitly addressed through comments related to a growth mindset and a belief that both students and teachers should be allowed autonomy and support in trying new things.

Notably, discussion related to *CC3. Integrated, Innovative Technology Use* focused almost entirely on makerspaces. Given the widespread disagreement about the role of technology in STEM education [15] and the fact that newly adopted technological tools often align closely with what is already done in classrooms [66], it is perhaps unsurprising that technology received little explicit discussion. Indeed, Holmlund et al. [67] found that few teachers, administrators, or STEM professional development providers discussed the use of technology as being key to their conceptualizations of STEM. However, it is also important to note that the administrators in this district viewed technology as an integral part of teaching and learning, rather than as a separate entity. As such, technologies including computers, coding, digital notebooks, and online collaborative tools were integrated into the daily instructional approaches through the use of reform-based teaching practices. Therefore, while the common discussion of *CC3* centered on the implementation of makerspaces within each school, the focus of the makerspaces was on *CC2* and the provision of quality learning experiences for students, rather than the specific technologies themselves.

With the foundation of flexibility and responsiveness associated with *CC9* and *CC12*, as well as the need for all teachers to become experts in *CC2* to enact the STEM mission, district leaders continually emphasized teachers' professional learning. This was financially possible because of the low level of curriculum investment needed with the view of STEM as a pedagogy, as well as through funding from *CC5. Business Partnerships*. Professional development and STEM certification opportunities were provided to all of the teachers and staff, even if they did not have the primary responsibility for teaching STEM disciplines. For example, art, music, and physical education teachers, as well as school principals, were STEM-certified, illustrating the shared responsibility for enacting STEM education. This commitment to *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff* was reemphasized each time a new school adopted a STEM focus, both through the provision of professional development opportunities and the positioning of John in the newest STEM school to provide on-site support. The relationship between John and the well-prepared faulty allowed for collaboration in designing, implementing, and evaluating STEM-focused lessons and units based on the existing district resources and materials.

Conceptualizing STEM as a pedagogy was also related to *CC12. Innovative and Responsive Leadership*. Some level of resistance to change is expected in educational reforms, particularly when teachers view new initiatives as threatening [68]. However, in this district, teachers were not asked to adopt a new STEM curriculum or completely abandon their current instructional materials. Rather, they were encouraged to "STEMify" their teaching by utilizing research-based best practices. Evidence of positive results can actually be more important than initial teacher buy-in [69], which was the case with this district. By the time the students reached middle school, both teachers and administrators could identify students who had attended Elementary A based on their mindset and approach to learning compared to the students who had attended the non-STEM elementary schools. This qualitative, observational data informed their decision to expand the STEM mission, which was related to *CC11. Data-Driven Decision Making for Continuous Improvement*. District leaders' approach to the promotion of change and growth among teachers who may have otherwise been resistant to the STEM mission allowed for change to become visible through observable benefits to students.

CC16. Sustainability was attended to on many occasions as the district's STEM mission expanded to include additional schools. The distribution of leadership among administrators and teachers promoted sustained change [46], and John became a key individual in spreading a consistent approach to STEM across the district. By physically locating his office in the newest STEM schools, the teachers who were least familiar with STEM had direct access to him for coaching and other support. His shifting office location also served to support the distribution of leadership responsibilities among the teachers at the established STEM schools. Once John moved from a school location, the teachers were more reliant upon one another and the expertise located within their buildings, allowing STEM teacher leaders to emerge. A focus on *CC16. Sustainability* can also be seen in some of the district hiring decisions. Two of the current principals received their STEM certifications through the district when they were teachers, and by hiring them to fill leadership positions, there is increased continuity and alignment in relation to the STEM mission. In addition, these key decisions highlight *CC12. Innovative and Responsive Leadership*. The school and district leaders were proactive in ensuring that teachers and students had the support they needed. For example, by combining literacy and STEM coaching, the instructional coach position was more resistant to changes due to shifts in funding or district initiatives. In another example of both *CC12* and *CC16*, some principals chose to reassign teachers in their schools to different grade levels or cross-curricular teams. While these decisions were not necessarily popular with the teachers, they served to distribute STEM expertise among the staff with the goal of fostering the spread and sustainability of the STEM mission.

An interesting connection between *CC16. Sustainability*, *CC15. Community and Family Involvement* and *CC8. Inclusive STEM Mission* emerged in this study. Because elementary school enrollment was determined based on students' home addresses, students in the Elementary A zone received first access to STEM instruction. However, families of students attending the other schools expressed strong opinions in the determination of whether their children would have a STEM-focused education, and advocated for a more inclusive approach. It quickly became apparent that limiting STEM education to one elementary and select middle school teams was not sufficient to meet community and family demands, pushing the district to scale the STEM focus. Interestingly, the path to inclusivity differed from what often occurs in education. In this case, Elementary A had a student population that was more socioeconomically disadvantaged than the other elementary schools, and given its "failing" status on standardized tests, it was the first elementary school to adopt the STEM mission. It was the parents and teachers at the more affluent schools that pushed for more STEM schools, and district administrators recognized the need for inclusion. Multiple participants in this study expressed the sentiment that a student's home address or zip code should not determine the quality of education they received. With a firm belief that STEM instruction was beneficial to all students, the district moved forward in ensuring access to STEM for all students.

With 11 different administrators participating in this study, the distributed nature of the leadership within the district was readily apparent. Each individual played different, but important, roles in the development, enactment, and sustainability of the district's STEM mission. While some leaders focused primarily on macro-functions, others also performed micro-leadership tasks [48]. Tammy and other school board members provided macro-level support for STEM, making sure that the structures were in place for the mission to be carried out. With these structures in place, the school board allowed others to attend to the specifics of the STEM mission. Mike became the district superintendent after the STEM mission was already underway, but one of his key leadership contributions was bringing attention equity at a macro-level. This included revising the district's mission statement to explicitly focus on equity, as well as advocating for the expansion of STEM to all schools and all students in the name of equity. Mike also distributed responsibility for STEM-related decisions to the school-level teams, allowing each school autonomy in the development of its specific approach to STEM instruction. As the district's Director of Teaching and Learning, Lisa maintained a macro-level perspective of the curriculum and instruction across all of the content areas. For example, she attended to literacy in the school district, ensuring that the STEM focus did not detract from literacy initiatives. Perhaps more than any other individual, John was a consistent STEM advocate in the district. As the STEM Coordinator, he attended to both macro- and micro-leadership functions. At the macro-level, he established business partnerships that led to funding for STEM efforts and organized formal professional development opportunities like STEM certifications for teachers. However, he also led at the micro-level, working with individual teachers to provide day-to-day support related to STEM instruction. While John undoubtedly played a central leadership role in the district's STEM initiative, he, too, ensured that the principals and teachers shared in the leadership responsibilities.

Each school principal held key responsibilities in advancing the district's STEM mission at both the macro-and micro-levels within their schools. David provided school-level leadership for the district's first STEM school (Elementary A), including researching approaches to STEM instruction and fostering the belief that STEM should be embedded in all disciplines. He also distributed leadership to key individuals in the school, including his innovative approach to instructional coaching that included pairing literacy and STEM coaches to support teachers as a team. Daniel became the leader of Elementary A after it had already been designated as a STEM school. While the mission was already being enacted at the school, Daniel focused on developing a shared vision for STEM instruction, including emphasizing a growth mindset, higher-order thinking, and real-world applications across disciplines. There was a parallel transition of leadership at the intermediate and middle schools. Eric was the first school leader, and faced unique challenges related to teachers' resistance to change and concerns about equity for both students and teachers, given the school's split focus, with only some sections focusing on STEM. Eric's key roles included overcoming these obstacles; for example, he developed a lottery system for admission to the STEM sections of the intermediate school. As the intermediate school was reorganized as a middle school with grades 6–8 in one building, Laura became the school leader. She led the school community through this transition, including assessing the needs of various school stakeholders (teachers, students, parents). Jennifer, Heather, and Kelly were already serving in principal positions when their schools adopted the STEM focus. However, even prior to the formal designation as STEM schools, all three of these elementary principals started some level of STEM programming, such as makerspaces. As their schools became more fully immersed in STEM instruction, these leaders replicated key aspects from Elementary A while also determining how STEM education would be unique at their schools. This included capitalizing on the experiences of Elementary A teachers to support teachers at Elementary B, C, and D. For example, teachers from Elementary A worked with colleagues teaching the same grade level at the other schools, and shared lessons, instructional techniques, assessments, and encouragement. The expansion of the STEM mission also included distributing leadership to teachers at Elementary B, C, and D, and providing them with agency in determining the nuances of their own approach to STEM instruction.

8. Limitations

Like all studies, there are limitations associated with this research. First, the views highlighted in this study are those of administrators. It is possible that teachers, students, family members, and community members would emphasize different CCs when talking about the district's STEM mission. Leadership responsibilities were certainly distributed across teachers and other individuals within the district, but a full examination of these individuals' views was beyond the scope of this study.

Second, the CCs were originally developed based on STEM high schools that had already been established as exemplars of STEM education [18,19]. The schools involved in these previous studies were defined as inclusive STEM high schools, with an explicit focus on equity and an application process for admission to the schools. We also included CCs developed for elementary schools [53] in the present study. The contextual differences between the original CC research and the current study likely contributed to some of the patterns we saw. For example, there was no mention of specifics related to *CC10. Supports for Underrepresented Students*. While this is a central component of the inclusive STEM high schools, given their focus on historically underrepresented youth who may be unprepared for rigorous STEM instruction, it may be less apparent in schools with attendance based on neighborhood school zones.

9. Conclusions

Given the dearth of research on the process of developing, enacting, and sustaining a district-wide STEM mission, this study addresses a gap in the literature and provides insight that may be useful to researchers, as well as other schools or districts, developing a STEM focus. The CCs, while not an explicit part of the STEM visioning process for this district, provided a useful lens for the consideration of the shifting importance of different elements throughout the process.

Our use of the CCs in a public school district developing a STEM mission and admitting students based on attendance zones rather than an application process represents a new application of the CCs. With 16 different components, it was impossible to give equal attention to all of the components simultaneously. Through this study, we have identified several CCs that were central to the development of the public school district STEM mission. First, *CC12. Innovative and Responsive Leadership* was clearly central in developing, enacting, and sustaining the district's STEM mission. Strategic decisions that responded to the needs of students, teachers, families, and the community ensured widespread support for the

STEM mission. Second, *CC7. Well-Prepared STEM Teachers and Professionalized Teaching Staff* was critical throughout the period of study. Teachers, administrators, and school staff had access to a number of STEM-focused professional development opportunities with the goal of developing a well-qualified staff who shared joint responsibility for the STEM mission. Finally, *CC2. Reformed Instructional Strategies and Project-Based Learning* received ongoing focus. As the teachers modified their instructional practices and curriculum to better align with the STEM mission, reformed instructional practices were emphasized across all of the disciplines.

While these three CCs received ongoing focus and were particularly important in advancing the district's STEM mission, some CCs identified in the original studies of exemplary STEM high schools were less central in this district. For example, *CC4. STEM-Rich Informal Experiences* was rarely discussed. Perhaps this CC is more critical at the high school level than at the elementary or middle school levels. As previously described, *CC10. Supports for Underrepresented Students* was also less explicit than the other CCs. Again, the context of the present study likely related to the reduced emphasis on this element. By focusing on different CCs at different times and prioritizing several key CCs throughout, this district was able to achieve its goal of providing STEM instruction to all students in grades K–8. Although each school had agency in determining its own approach to STEM, John's role as the STEM coordinator working closely with teachers ensured consistency in the overarching district philosophy of STEM education as a pedagogical approach. This view had implications for which CCs were emphasized, and ultimately provided a roadmap for how the district moved forward with its STEM mission. As schools and districts develop, enact, and sustain their STEM mission, it is important to consider the contextual factors that may influence the relative importance of the CCs. As shown by this district, it is possible to create a STEM school that meets the goals of its stakeholders without explicit attention to every CC originally identified by Peters-Burton et al. [18] and Lynch et al. [19].

Author Contributions: Conceptualization, J.R.W., G.H.R., E.A.R.-W. and T.M.; methodology, J.R.W., G.H.R. and E.A.R.-W.; formal analysis, J.R.W., G.H.R. and E.A.R.-W.; writing—original draft preparation, J.R.W.; writing—review and editing, J.R.W., G.H.R., E.A.R.-W. and T.M.; visualization, J.R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and the protocol was approved by the Institutional Review Board of the University of Minnesota (1604E86171, 19 May 2016).

Informed Consent Statement: All participants gave their informed consent for inclusion before they participated in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data will be blinded, and any identifying information will be removed prior to sharing.

Conflicts of Interest: The fourth author is an employee of the district featured in this study. To avoid bias, he did not conduct interviews or participate in the formal analysis process.

References

1. NGSS Lead States. *Next Generation Science Standards: For States, by States*; National Academies Press: Washington, DC, USA, 2013.
2. National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, USA, 2012.
3. National Science Teaching Association. Available online: https://ngss.nsta.org/about.aspx (accessed on 14 August 2021).
4. President's Council of Advisors on Science and Technology. *Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future*; Executive Office of the President: Washington, DC, USA, 2010.
5. National Research Council (U.S.). *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics*; National Academies Press: Washington, DC, USA, 2011. [CrossRef]

6. Breiner, J.M.; Harkness, S.S.; Johnson, C.C.; Koehler, C.M. What Is STEM? A Discussion About Conceptions of STEM in Education and Partnerships: What Is STEM? *Sch. Sci. Math.* **2012**, *112*, 3–11. [CrossRef]
7. Brown, R.; Brown, J.; Reardon, K.; Merrill, C. Understanding STEM: Current Perceptions. *Technol. Teach.* **2011**, *70*, 5–9.
8. Bybee, R.W. *The Case for STEM Education: Challenges and Opportunities*; National Science Teachers Association: Arlington, VA, USA, 2013.
9. English, L.D. STEM Education K-12: Perspectives on Integration. *Int. J. STEM Educ.* **2016**, 3. [CrossRef]
10. Johnson, C.C. Four Key Premises of STEM. *Sch. Sci. Math.* **2012**, *112*, 1–2. [CrossRef]
11. Koehler, C.; Binns, I.C.; Bloom, M.A. The Emergence of STEM. In *STEM Road Map: A Framework for Integrated STEM Education*; Johnson, C.C., Peters-Burton, E.E., Moore, T.J., Eds.; Routledge: New York, NY, USA, 2016; pp. 13–22.
12. Ring, E.A.; Dare, E.A.; Crotty, E.A.; Roehrig, G.H. The Evolution of Teacher Conceptions of STEM Education Throughout an Intensive Professional Development Experience. *J. Sci. Teach. Educ.* **2017**, *28*, 444–467. [CrossRef]
13. Baldinger, E.E.; Staats, S.; Covington Clarkson, L.M.; Gullickson, E.C.; Norman, F.; Akoto, B. A Review of Conceptions of Secondary Mathematics in Integrated STEM Education: Returning Voice to the Silent M. In *Integrated Approaches to STEM Education*; Anderson, J., Li, Y., Eds.; Advances in STEM Education; Springer Nature: Cham, Switzerland, 2020; pp. 67–90. [CrossRef]
14. Coad, L. The M in STEM: What Is It Really? *Aust. Math. Teach.* **2016**, *72*, 3–6.
15. Ellis, J.; Wieselmann, J.; Sivaraj, R.; Roehrig, G.; Dare, E.; Ring-Whalen, E. Toward a Productive Definition of Technology in Science and STEM Education. *Contemp. Issues Technol. Teach. Educ.* **2020**, *20*, 472–496.
16. Crotty, E. Understanding the Ways in Which Teacher Leadership Teams Influence STEM Integration in Emerging STEM Schools. Ph.D. Thesis, University of Minnesota, Minneapolis, MN, USA, 2018.
17. LaForce, M.; Noble, E.; King, H.; Century, J.; Blackwell, C.; Holt, S.; Ibrahim, A.; Loo, S. The Eight Essential Elements of Inclusive STEM High Schools. *Int. J. STEM Educ.* **2016**, *3*, 21. [CrossRef]
18. Peters-Burton, E.E.; Lynch, S.J.; Behrend, T.S.; Means, B.B. Inclusive STEM High School Design: 10 Critical Components. *Theory Pract.* **2014**, *53*, 64–71. [CrossRef]
19. Lynch, S.J.; Burton, E.P.; Behrend, T.; House, A.; Ford, M.; Spillane, N.; Matray, S.; Han, E.; Means, B. Understanding Inclusive STEM High Schools as Opportunity Structures for Underrepresented Students: Critical Components. *J. Res. Sci. Teach.* **2018**, *55*, 712–748. [CrossRef]
20. Means, B.; House, A.; Young, V.; Wang, H.; Lynch, S. Expanding Access to STEM-Focused Education: What Are the Effects? In Proceedings of the NARST Annual International Conference, Rio Grande, Puerto Rico, 1 April 2013.
21. National Science Foundation. *Women, Minorities, and Persons with Disabilities in Science and Engineering*; NSF 21-321; National Center for Science and Engineering Statistics: Alexandria, VA, USA, 2021.
22. Means, B.; Confrey, J.; House, A.; Bhanot, R. *STEM High Schools: Specialized Science Technology Engineering and Mathematics Secondary Schools in the U.S.*; SRI Project P17858; SRI International: Menlo Park, CA, USA, 2008.
23. Young, V.M.; House, A.; Wang, H.; Singleton, C.; Klopfenstein, K. *Inclusive STEM Schools: Early Promise in Texas and Unanswered Questions*; National Research Council: Washington, DC, USA, 2011.
24. Wiswall, M.; Stiefel, L.; Schwartz, A.E.; Boccardo, J. Does Attending a STEM High School Improve Student Performance? Evidence from New York City. *Econ. Educ. Rev.* **2014**, *40*, 93–105. [CrossRef]
25. Franco, M.S.; Patel, N.H.; Lindsey, J. Are STEM High School Students Entering the STEM Pipeline? *NCSSSMST J.* **2012**, *17*, 14–23.
26. Means, B.; Wang, H.; Young, V.; Peters, V.L.; Lynch, S.J. STEM-focused High Schools as a Strategy for Enhancing Readiness for Postsecondary STEM Programs. *J. Res. Sci. Teach.* **2016**, *53*, 709–736. [CrossRef]
27. Erdogan, N.; Stuessy, C. Examining the Role of Inclusive STEM Schools in the College and Career Readiness of Students in the United States: A Multi-Group Analysis on the Outcome of Student Achievement. *Educ. Sci. Theory Pract.* **2015**, *15*, 1517–1529. [CrossRef]
28. Eisenhart, M.; Weis, L.; Allen, C.D.; Cipollone, K.; Stich, A.; Dominguez, R. High School Opportunities for STEM: Comparing Inclusive STEM-Focused and Comprehensive High Schools in Two US Cities. *J. Res. Sci. Teach.* **2015**, *52*, 763–789. [CrossRef]
29. Gnagey, J.; Lavertu, S. The Impact of Inclusive STEM High Schools on Student Achievement. *AERA Open* **2016**, 2. [CrossRef]
30. Kushnir, N.; Osipova, N.; Valko, N.; Kuzmich, L. Review of Trends, Approaches and Perspective Practices of STEM-Education for Training Center Opening. *Inf. Technol. Educ.* **2017**, *31*, 69–80. [CrossRef]
31. Knipprath, H.; Thibaut, L.; Buyse, M.-P.; Ceuppens, S.; De Loof, H.; De Meester, J.; Goovaerts, L.; Struyf, A.; Boeve-De Pauw, J.; Depaepe, F.; et al. STEM Education in Flanders: How STEM@school Aims to Foster STEM Literacy and a Positive Attitude Towards STEM. *IEEE Instrum. Meas. Mag.* **2018**, *21*, 36–40. [CrossRef]
32. Osadchyi, V.V.; Valko, N.V.; Kushnir, N.O. Design of the Educational Environment for STEM-Oriented Learning. *Inf. Technol. Learn. Tools* **2020**, *75*, 316–330.
33. Ortega, V.I. Increasing STEM Exposure in K-5 Schools through Makerspace Use: A Multi-Site Early Success Case Study. Ph.D. Thesis, University of California Los Angeles, Los Angeles, CA, USA, 2017.
34. Slavit, D.; Nelson, T.H.; Lesseig, K. The Teachers' Role in Developing, Opening, and Nurturing an Inclusive STEM-Focused School. *Int. J. STEM Educ.* **2016**, *3*, 1–17. [CrossRef]
35. Leammukda, F.D.T. An In-Depth Focus on An Emerging STEM School: A Community-Based Framework for STEM Integration. Ph.D. Thesis, University of Minnesota, Minneapolis, MN, USA, 2020.

36. Williams, R. STEM Implementation: A Case Study of a Primary Grade School. Ph.D. Thesis, American College of Education, Indianapolis, IN, USA, 2019.
37. Sikma, L.; Osborne, M. Conflicts in Developing an Elementary STEM Magnet School. *Theory Pract.* **2014**, *53*, 4–10. [CrossRef]
38. Siegel, D.; Giamellaro, M. Defining STEM within a School District: A Co-Constructed and Evolving Process. *Cult. Stud. Sci. Educ.* **2020**, *15*, 739–773. [CrossRef]
39. Siegel, D.; Giamellaro, M. Non-STEM Teachers Finding Their Place in STEM. *J. Sci. Teach. Educ.* **2021**. [CrossRef]
40. El Nagdi, M.; Leammukda, F.; Roehrig, G. Developing Identities of STEM Teachers at Emerging STEM Schools. *Int. J. STEM Educ.* **2018**, *5*, 1–13. [CrossRef] [PubMed]
41. Rissmann-Joyce, S.; El Nagdi, M. A Case Study: Egypt's First STEM Schools: Lessons Learned. In Proceedings of the Global Summit on Education, Kuala Lumpur, Malaysia, 11–12 March 2013.
42. El Nagdi, M.; Roehrig, G. Identity Evolution of STEM Teachers in Egyptian STEM Schools in a Time of Transition: A Case Study. *Int. J. STEM Educ.* **2020**, *7*, 1–16. [CrossRef]
43. Leithwood, K.; Harris, A.; Hopkins, D. Seven Strong Claims about Successful School Leadership. *Sch. Leadersh. Manag.* **2008**, *28*, 27–42. [CrossRef]
44. Leithwood, K.; Harris, A.; Hopkins, D. Seven Strong Claims about Successful School Leadership Revisited. *Sch. Leadersh. Manag.* **2020**, *40*, 5–22. [CrossRef]
45. Gronn, P. Distributed Leadership as a Unit of Analysis. *Leadersh. Q.* **2002**, *13*, 423–451. [CrossRef]
46. Hargreaves, A.; Fink, D. Sustaining Leadership. *Phi Delta Kappan* **2003**, *84*, 693–700. [CrossRef]
47. Woods, P.A.; Roberts, A. Distributed Leadership and Social Justice: Images and Meanings from across the School Landscape. *Int. J. Leadersh. Educ.* **2016**, *19*, 138–156. [CrossRef]
48. Spillane, J.P.; Halverson, R.; Diamond, J.B. Investigating School Leadership Practice: A Distributed Perspective. *Educ. Res.* **2001**, *30*, 23–28. [CrossRef]
49. Heck, R.H.; Hallinger, P. Testing a Longitudinal Model of Distributed Leadership Effects on School Improvement. *Leadersh. Q.* **2010**, *21*, 867–885. [CrossRef]
50. Leithwood, K.; Mascall, B. Collective Leadership Effects on Student Achievement. *Educ. Adm. Q.* **2008**, *44*, 529–561. [CrossRef]
51. Seashore Louis, K.; Dretzke, B.; Wahlstrom, K. How Does Leadership Affect Student Achievement? Results from a National US Survey. *Sch. Eff. Sch. Improv.* **2010**, *21*, 315–336. [CrossRef]
52. Hallinger, P.; Heck, R.H. Collaborative Leadership and School Improvement: Understanding the Impact on School Capacity and Student Learning. *Sch. Leadersh. Manag.* **2010**, *30*, 95–110. [CrossRef]
53. Peters-Burton, E.E.; House, A.; Peters, V.; Remold, J. Understanding STEM-focused Elementary Schools: Case Study of Walter Bracken STEAM Academy. *Sch. Sci. Math.* **2019**, *119*, 446–456. [CrossRef]
54. Clandinin, D.J. Living, Telling, and Retelling: Processes of Narrative Inquiry. In *Engaging in Narrative Inquiry*; Routledge: London, UK, 2013; pp. 9–31.
55. Clandinin, D.J. *Journeys in Narrative Inquiry: The Selected Works of D. Jean Clandinin*; Routledge: New York, NY, USA, 2020.
56. Clandinin, D.J.; Connelly, F.M. *Narrative Inquiry: Experience and Story in Qualitative Research*, 1st ed.; 1. PB Print; The Jossey-Bass Education Series; Jossey-Bass: San Francisco, CA, USA, 2000.
57. Dewey, J. *Experience and Education*; Collier Books: New York, NY, USA, 1938.
58. Clandinin, D.J.; Rosiek, J. Mapping a Landscape of Narrative Inquiry: Borderland Spaces and Tensions. In *Handbook of Narrative Inquiry: Mapping a Methodology*; Clandinin, D.J., Ed.; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2007; pp. 35–76. [CrossRef]
59. Connelly, F.M.; Clandinin, D.J. Narrative Inquiry. In *Handbook of Complementary Methods in Education Research*; Green, J.L., Camilli, G., Elmore, P.B., American Educational Research Association, Eds.; Lawrence Erlbaum Associates: Washington, DC, USA, 2006; pp. 477–487.
60. Clandinin, D.J.; Caine, V. Narrative Inquiry. In *Reviewing Qualitative Research in the Social Sciences: A Guide for Researchers and Reviewers*; Trainor, A.A., Graue, E., Eds.; Routledge: New York, NY, USA, 2012; pp. 166–179.
61. Mishler, E.G. *Research Interviewing: Context and Narrative*; Harvard University Press: Cambridge, MA, USA, 1986.
62. Polkinghorne, D.E. Narrative Configuration in Qualitative Analysis. *Qual. Stud. Educ.* **1995**, *8*, 5–23. [CrossRef]
63. National Center for Education Statistics. Available online: https://nces.ed.gov/ccd/districtsearch/index.asp (accessed on 14 August 2021).
64. Patton, M.Q. *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2015.
65. Corbin, J.M.; Strauss, A.L. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*, 4th ed.; SAGE: Los Angeles, CA, USA, 2015.
66. Putnam, R.T.; Borko, H. What Do New Views of Knowledge and Thinking Have to Say about Research on Teacher Learning? *Educ. Res.* **2000**, *29*, 4–15. [CrossRef]
67. Holmlund, T.D.; Lesseig, K.; Slavit, D. Making Sense of "STEM Education" in K-12 Contexts. *Int. J. STEM Educ.* **2018**, *5*, 32. [CrossRef]

68. Tschannen-Moran, M.; Chen, J.A. Focusing Attention on Beliefs about Capability and Knowledge in Teachers' Professional Development. In *Handbook of Professional Development in Education: Successful Models and Practices, PreK-12*; Martin, L.E., Kragler, S., Quatroche, D.J., Bauserman, K.L., Hargreaves, A., Eds.; Guilford Press: New York, NY, USA, 2014; pp. 246–264.
69. Guskey, T.R. Professional Development and Teacher Change. *Teach. Teach.* **2002**, *8*, 381–391. [CrossRef]

education sciences

Article

Computer Science beyond Coding: Partnering to Create Teacher Cybersecurity Microcredentials

Andrea C. Burrows [1,*], Mike Borowczak [2] and Bekir Mugayitoglu [1]

[1] School of Teacher Education, University of Wyoming, Laramie, WY 82071, USA; bmugayit@uwyo.edu
[2] Department of Computer Science, University of Wyoming, Laramie, WY 82071, USA; Mike.Borowczak@uwyo.edu
* Correspondence: andrea.burrows@uwyo.edu

Abstract: Computer science, cybersecurity education, and microcredentials are becoming more pervasive in all levels of the educational system. The purpose of this study was partnering with precollegiate teachers: (1) to investigate the self-efficacy of 30 precollegiate teacher participants towards computer science before, during, and after three iterations of a cybersecurity microcredential, and (2) to make changes to the cybersecurity microcredential to improve its effectiveness. The authors explored what teachers need in a microcredential. The first Cohort (n = 5) took the microcredential sequence over 28 days in the summer of 2020, the second Cohort (n = 16) took it over 42 days in the fall of 2020, and the third Cohort (n = 9) took it over 49 days in the summer of 2021. The authors investigated three research questions and used a systems thinking approach while developing, evaluating, and implementing the research study. The researchers used quantitative methods in the collection of a self-efficacy subscale survey to assess whether the precollegiate teachers' beliefs about computer science changed, and then used qualitative methods when conducting semi-structured teacher participant interviews to address the research questions. The findings show that the precollegiate teachers' self-efficacy scores towards computer science increased, and that there are areas in need of attention, such as resources and implementation, when creating microcredentials. The implications of this research include the importance of purposefully crafting microcredentials and professional developments, including aspects of creating effective partnerships.

Keywords: microcredential; cybersecurity education; computer science; systems thinking; precollegiate teachers; self-efficacy; STEM; coding; partnership; professional development

Citation: Burrows, A.C.; Borowczak, M.; Mugayitoglu, B. Computer Science beyond Coding: Partnering to Create Teacher Cybersecurity Microcredentials. *Educ. Sci.* **2022**, *12*, 4. https://doi.org/10.3390/educsci12010004

Academic Editor: João Piedade

Received: 12 November 2021
Accepted: 14 December 2021
Published: 22 December 2021

1. Challenge in Science Teacher Education

Throughout 2020 and 2021, primarily due to the ongoing COVID-19 pandemic, virtual learning became a reality for many people, including precollegiate students [1,2]. While the pandemic has adversely affected students, it has also impacted precollegiate teachers' access to professional development (PD) at local, national, and international levels [3]. To retain access to PDs, many precollegiate PD providers and teachers moved from holding in-person PDs to virtual PDs. Virtual PDs can offer new formats such as microcredentials [4]. The microcredential module set discussed throughout this work was developed with partners spanning a state department of education, a state university, industry partners, and teacher practitioners. Microcredentials provide teachers an opportunity to learn and complete materials asynchronously at their own pace. Instead of the continuous day-long or week-long instruction which occurs in many PDs, microcredentials are virtual, self-paced, and allow flexibility over longer periods of time [5–8]. With this in mind, one challenge is finding out how precollegiate teachers perceive a cybersecurity microcredential PD, how it impacts their self-efficacy, and how the most effective microcredential can be coconstructed. The concept of an effective microcredential is important because educational researchers recognize that learning the principles of computer science (CS), computational thinking, and cybersecurity promote thinking creatively [9–12], and this can benefit disciplinary integration within Science, Technology, Engineering, and Mathematics (STEM) [13,14].

While microcredentials may ultimately take the form of a digital badge, regardless of their representation, they serve as evidence of a skill or learning [15], and this research study involved microcredential modules, specifically about cybersecurity, as they are embedded within computer science content. Computer science is, at its core, problem solving, or specifically, how to manipulate computational devices to solve problems with data. Although many not acquainted with computer science might think that it focuses solely on coding [16], and there are research studies focused on teaching coding [17], there are computer science skills that can be taught at any age or grade level, both with and without a computer [18,19].

Though cybersecurity is traditionally thought of as a subfield of computer science, focused on the security of devices, the field focuses on all aspects of securing computing systems—from politics, psychology, ethics, and society implications to how information is stored, processed, and transmitted. Cybersecurity's focus ranges from how individuals interact with traditional computing devices to how to insure advanced and distributed systems support modern-day society [20]. The broader field of security has always been a highly interdisciplinary and integrated field, requiring domain experts from the social sciences as well as the STEM fields to model, predict, investigate, understand, and prevent attacks [21,22]. Depending on the specific cybersecurity problems, it can require knowledge that includes but is not limited to:

Science—an understanding of physical, chemical, and electrical systems and device physics;

Technology—computing systems, networks, communication infrastructure, and mobile devices;

Engineering—system designs, problem solving, and constraint/resilient infrastructure;

Mathematics—logic, modeling, and algorithms; encryption/encoding, information theory, set theory, and quantum computing.

In many practical instances, solving cybersecurity challenges requires a transdisciplinary approach, where disciplines cannot be easily teased apart and require the knowledge of multiple spaces simultaneously. In educational realms, this can be emulated in interdisciplinary challenges and projects [10,23]. Educational literature shows that, in general, if you teach 'something', that the participants will generally learn 'something' and also like it more along the way [24,25]. An online PD study showed that areas in need of attention include matching PDs to the teachers' backgrounds, aligning the PD with curricula, and using motivational design to enhance teacher engagement [26]. The authors of this article investigated alignment with these concepts within computer science and cybersecurity, partnered with precollegiate teachers, and probed teacher needs in the microcredential.

2. The Framework

In approaching the problem of a microcredential's impact while creating a more effective microcredential model, the authors used a systems thinking framework. The systems thinking framework considers the end-user's experience, in this case, precollegiate CS and STEM teachers, as well as the problem to be solved [27,28]. This approach is started by identifying the common problems/barriers to implementation, and in this study the authors used it to identify the needs of precollegiate teachers. The systems thinking framework assists in identifying the problem, in this case, the interaction of precollegiate teachers with other human factors and their interactions with the microcredential platform and resources. The end stage of systems thinking covers the needs of the user beyond merely solving the problem [29]. Systems thinking does not break the process down into pieces, but instead keeps everything connected [30]. Therefore, the authors used the systems thinking framework to focus on possible factors such as a user-friendly platform, content-richness, and competency-based, cybersecurity-friendly pedagogies to meet the main problems of crafting an effective and efficient microcredential product [9,10,31].

The authors of this work prototyped and tested three microcredential iterations (called Pilot 1, 2, and 3), each with multiple modules, to investigate a cybersecurity microcredential's impact on precollegiate teachers and to explore what makes a high-quality microcredential. The authors posit that a high-quality microcredential would include user-friendly spaces, content-rich resources, and use a mastery-based approach in a microcredential for precollegiate CS and STEM teachers. Microcredential prototype processes were envisioned to be teacher-oriented. In particular, beliefs, behaviors, and emotions were important considerations of the microcredential development process. The precollegiate teachers were also included in the development process as partners, as their feedback, insights, emotions, and behaviors were all considered by the authors.

3. Study and Research Questions

Computer science, cybersecurity education, and microcredentials are becoming more pervasive in all levels of the educational system [4,10]. The purpose of this study was twofold: (1) to investigate the self-efficacy of 30 precollegiate teacher participants towards computer science before, during, and after three iterations of a cybersecurity microcredential and (2) to make changes to the microcredential to improve its effectiveness. To address these issues, the following research questions were explored:

Research Question 1 (RQ1). *How does a cybersecurity microcredential impact precollegiate teachers' computer science self-efficacy?*

Research Question 2 (RQ2). *How much time do precollegiate teachers spend in a microcredential?*

Research Question 3 (RQ3). *How do precollegiate teachers shape a microcredential to be more effective for teacher needs?*

4. Methods and Analysis

The authors used both quantitative measures (survey responses for precollegiate teacher self-efficacy) and qualitative measures (semistructured interviews for microcredential suggestions). The study involved 30 self-selected precollegiate teacher participants across three Cohorts, and these participants included 22 females (73%) and 8 males (27%). Most of them were teaching multiple subjects including mathematics (53%), science (47%), CS (30%), literacy/English (27%), all STEM disciplines (20%), and others (10%). These and other demographics are shown in Table 1, which express responses as a percentage of the total sample. In many cases, participants selected one or more answers and thus the sum of the percentages for any characteristic may add up to more than 100%.

Each cybersecurity microcredential iteration changed slightly based on the previous Cohort's suggestions (see Table 2). The cybersecurity microcredential consisted of a series of learning modules that covered the principles of cybersecurity (see Table 3), and each module contained clear learning objectives aligned with the Computer Science Teachers Association (CSTA) standards (https://www.csteachers.org/, accessed on 8 December 2021). The microcredential team created a variety of activities based on the CS and disciplinary standards. There were learning objectives within each module. Quantitatively, the researchers used a self-efficacy subscale survey (inspired by [32]) with 29 items to assess whether precollegiate teachers' beliefs towards CS changed or did not change. The teachers' beliefs surrounding CS were assessed on a scale from 0 to 5, where 0 was strongly disagree and 5 was strongly agree. Qualitatively, the researchers conducted semistructured interviews, transcribed the interviews, and coded for themes, while focusing on changes for microcredential improvement. Codes were determined using open (labeling of responses) and axial (connecting categories from the first step) coding. All participants signed a university approved Institutional Review Board (IRB) consent form to participate in the study.

Table 1. Demographics of combined microcredential Cohorts (n = 30).

Gender (n = 30)					
Female	73%			Male	27%
Subjects Taught (n = 30)					
Mathematics	53%	Science	47%	Computer Science	30%
Literacy/English	27%	STEM	20%	Other	10%
Levels Taught (n = 30)					
PreK–2	27%	3–5	37%	6–8	47%
9–12	37%	HE	3%		
Taken prior Cybersecurity Class/Course (n = 30)					
Yes	63%			No	37%
Years Teaching (Overall) (n = 30)					
0–3 years	7%	4–6 years	17%	7–10 years	10%
11–15 years	7%	16+ years	59%		
Years Teaching (CS) (n = 25)					
0–3 years	88%	4–6 years	12%	7–10 years	0%
11-15 years	0%	16+ years	0%		

Table 2. Summary of modules and features in Pilots 1, 2, and 3.

Component	Pilot 1	Pilot 2	Pilot 3
Modules	2	5	12
Required Modules: Details	2: Modules 0 and 1	3: Module 0 + Choose 2	3: Module 0 + Choose 2
Housed/Located	LMS/Canvas	LMS/Canvas	LMS/Canvas
Virtual Office Hours	2x/week—1hr slot	2x/week—1hr slot	By Request
Content Knowledge Quest.	No	Yes	Yes
Attitude Survey	No	Yes	Yes
Focus group & interviews	Yes	Yes	Yes
Bi-weekly progress reports	Yes	Yes	Yes
Duration	28 days	42 days	49 days
Participants	5	16	9
Resources	Custom resources and research materials.	More resources and research materials. Added sample lesson plans & computational thinking flashcards.	More resources, research materials, and sample lesson plans. Added design thinking flashcards and videos.

The first Cohort’s engagement in microcredential Pilot 1 was 28 days long, the second Cohort in Pilot 2 was engaged for 42 days, and Cohort 3 worked for 49 days. Each module in the course was grouped and organized to allow for scaffolded information for participant teachers as they progressed through the course. If participant teachers were to complete the entire cybersecurity microcredential, after completing Modules 0 and 1, participant teachers would choose between Modules 2 and 3; the same is true for the groupings of Modules 4 and 5, as well as the final grouping of Modules 6 through 12.

Table 3. Modules offered throughout the three Pilot experiences.

Module	Pilot 1	Pilot 2	Pilot 3
0	Intro to Cybersecurity	Intro to Cybersecurity	Intro to Cybersecurity
1	CIA Triad	CIA Triad	CIA Triad
2		Abstraction	Abstraction
3		Modularity	Data Hiding
4		Least Privilege	Simplicity
5			Minimization
6			Modularity
7			Domain Separation
8			Least Privilege
9			Layering
10			Resource Encapsulation
11			Process Isolation

The team expected that cybersecurity content would increase with each successive Cohort and that changes would be made based on teacher participant feedback. Cohort 1 (i.e., Pilot 1) consisted of an introduction to cybersecurity and the CIA triad (confidentiality, integrity, and accessibility), while Cohort 2 (i.e., Pilot 2) added three new modules including abstraction, least privilege, and modularity, and then Cohort 3 (i.e., Pilot 3) added seven new modules including data hiding, simplicity, minimization, domain separation, layering, resource encapsulation, and process isolation. The participant teachers worked for 28 days (Cohort 1, n = 5, summer 2020), 42 days (Cohort 2, n = 16, fall 2020), and 49 days (Cohort 3, n = 9, summer 2021) to complete the course material. The start of each Cohort/Pilot was defined by an introductory Zoom session, while the end was defined by debriefing meetings and then semistructured interviews. The precollegiate teachers completed the microcredential at their own pace within these timeframes. Additionally, the 29-question survey was provided for the precollegiate teachers before, during, and after the microcredential modules for Cohorts 2 and 3 (but not Cohort 1). In Cohort 2, of the 16 participants, all of them completed the pretest (16/16; 100%), and 11 participants completed the post-test survey (11/16; 69%). In Cohort 3, of the nine participants, seven completed the pretest (7/9; 78%), and five participants completed the post-test survey (5/9; 56%). The semistructured interviews were conducted after the debrief Zoom session at the end of the microcredential Cohort/Pilot, when the precollegiate teachers met with an interviewer (team member) and an observer (main instructor). Over all three Cohorts, nineteen precollegiate teachers were interviewed (19/30; 63%), and each interview was conducted online via Zoom within an approximately 30-min time frame, transcribed, and then coded as part of the larger set of data.

5. Findings and Participant Learning

5.1. Quantitative Findings

Overall, for Cohorts 2 and 3, precollegiate teacher self-efficacy improved after taking the cybersecurity microcredential. The authors present the evidence of self-efficacy towards CS for the cybersecurity microcredential from survey Questions 11 and 12 (see Figures 1 and 2). Question 11 (Figure 1) asked the teacher participants to respond to the following prompt: “I can effectively teach all students computer science” [16]. On the presurvey (n = 22), 68% (15/22) of the precollegiate teachers responded ‘strongly agree’ and ‘agree’ about their self-efficacy to teach computer science effectively in the classroom. On the postsurvey, the agreement (strongly agree and agree) increased to 86% (12/14). Question 12 (see Figure 2) asked teacher participants to respond to the following prompt: “I can teach the computer science concepts required by the curriculum” [25]. On the presurvey, 68% (15/22) of the precollegiate teachers responded ‘strongly agree’ and ‘agree’ about their self-efficacy to teach effectively in the classroom. On the postsurvey, 86% (12/14) of the precollegiate teachers responded ‘strongly agree’ and ‘agree’.

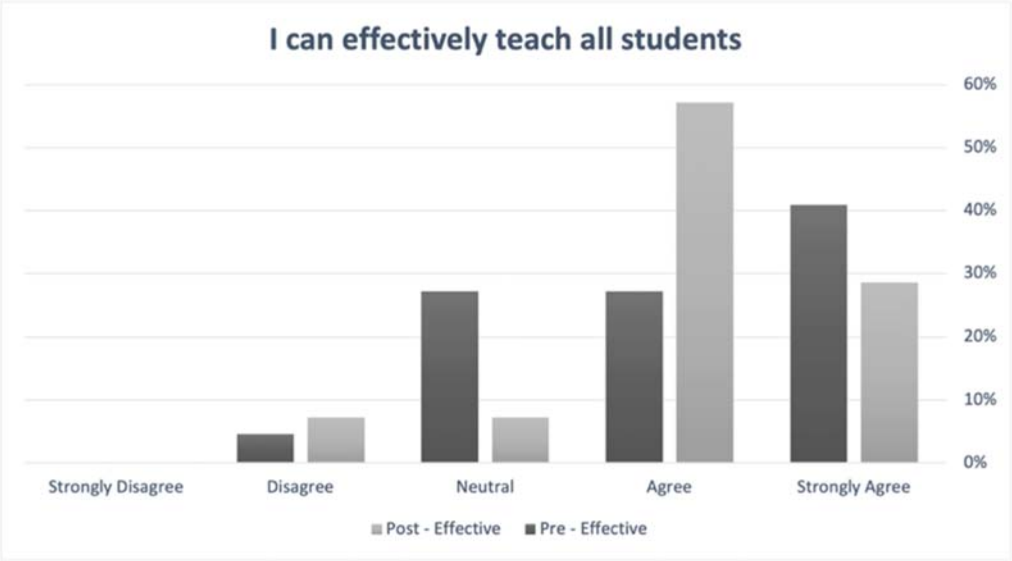


Figure 1. Question 11 from the self-efficacy survey, "I can effectively teach all students computer science".

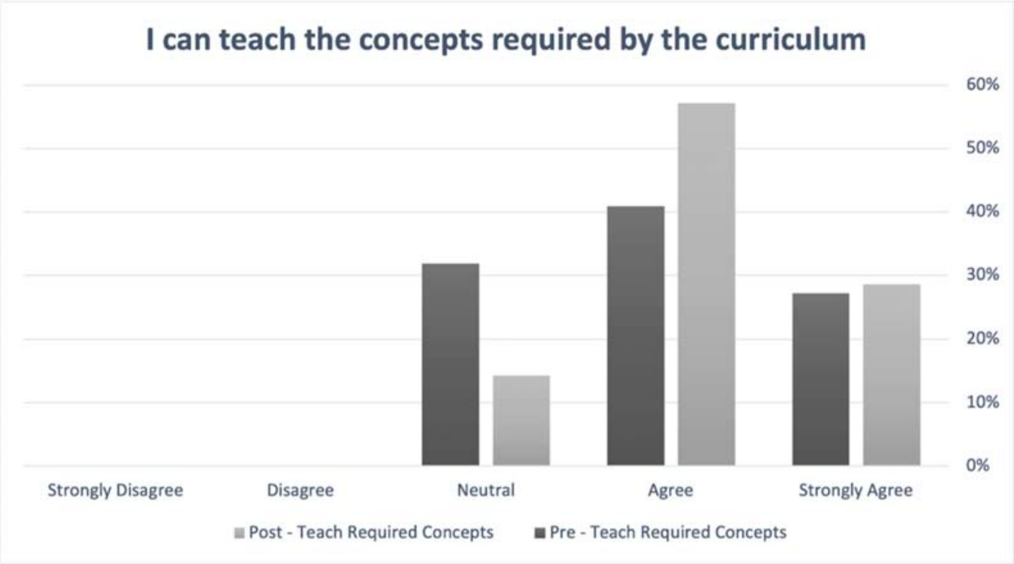


Figure 2. Question 12 from the self-efficacy survey, "I can teach the concepts required by the curriculum".

The time spent in the learning management system (LMS) for the microcredential varied widely. The LMS biweekly progress reports also showed self-reported use as varying widely (see Figure 3). The most time spent by a participant in the LMS was 192 h and least time spent was 2 h. The average time spent on the three modules was about 40 h. From the self-reported biweekly progress reports, the most time spent was 40 h and the least time spent was 6 h. The average time spent on the three modules was about 14 h. Given the drastic discrepancy between the maximum LMS reported time (192 h) and the corresponding self-reported progress report time (40 h), it is likely that a browser issue caused a session to remain open and inflate the time recorded by the LMS. This outlier was removed prior to any correlation analysis. Additionally, there was a weak, positive relationship between English/literacy teachers or high school educators and using the microcredential resources (including the LMS itself) for more time. Female teachers or STEM teachers were less likely to use the resources for long periods of time (or were more likely to use it for shorter durations).

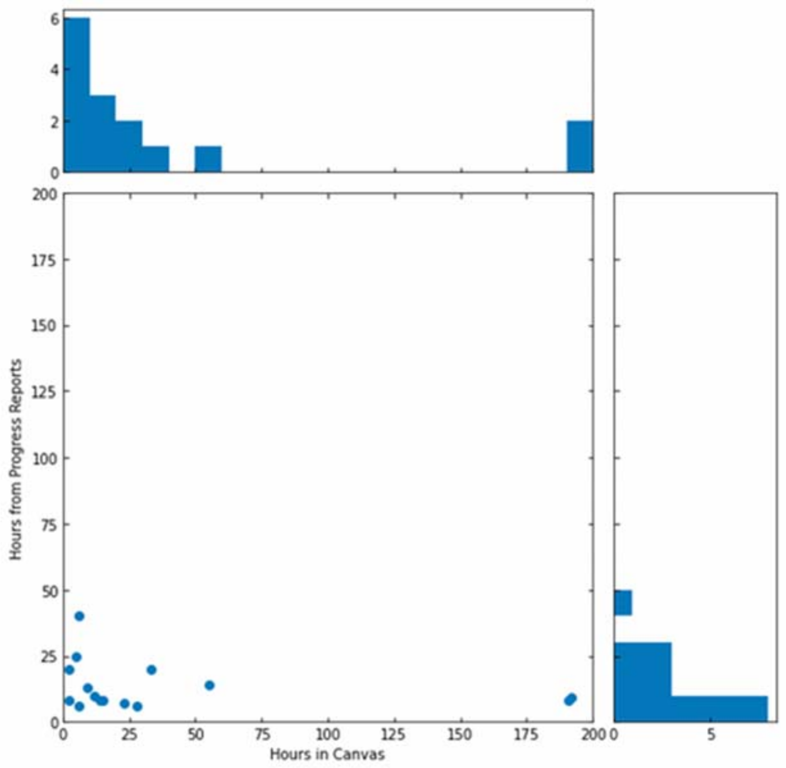


Figure 3. Time spent in the Canvas LMS (hours) versus time reported in biweekly progress report (hours). Note the outlier LMS reported time which was likely caused by a browser/LMS issue.

Importantly, there was a purposeful integration of disciplines and content, and some of the cybersecurity principles overlapped with computer programming and computational thinking concepts such as abstraction and modularity [17–22]. Therefore, the CS teachers who had prior programming knowledge spent less time than the STEM teachers who had never taken a programming course or had no prior programming knowledge. All precollegiate teachers took the introduction to cybersecurity module (Module 0), and this was included in the time spent by each participant. In addition, the precollegiate teachers were given the choice of which follow-on module to complete (Figure 4); 29% of the teachers chose the abstraction module, while only 2% of the teachers chose the minimization module.

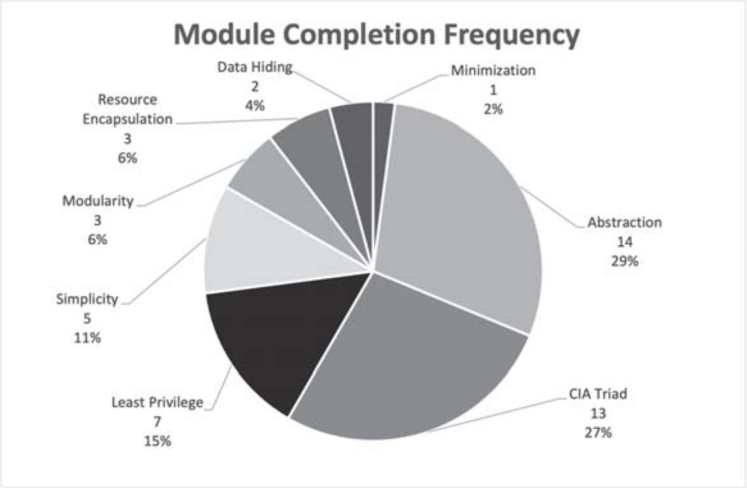


Figure 4. Modules selected and completed (n = 48).

5.2. Qualitative Findings

Overall, the authors conducted nineteen interviews over the three Cohorts. In coding the responses, two main themes surfaced. One was "Resources", and the second theme was "Implementation". Each main theme showed two subthemes, and these are described with examples in the following paragraphs.

For the main theme "Resources", the subthemes of "resources offered" and "resources used" were discovered. In the "resources offered" subtheme, the teachers most often referenced the flexibility to complete the microcredential in their own timeframe, community building, and the office hours.

For flexibility, one teacher commented, "microcredentialing was done at more of our own pace" (participant Cohort 1), and, "I like the flexibility to be able to do it whenever, it worked for me" (participant Cohort 2).

For community building, a teacher said, "I'm the only teacher, so it's really nice to make these connections and to talk with people, and [to] hear that I need to [use] computational thinking [explicitly in my classroom]" (participant Cohort 2). Another teacher commented, "I like the relationships . . . and getting to know [the teachers and microcredential team]" (participant Cohort 3).

For the office hours, the precollegiate teachers found the synchronous virtual office hour provided by the microcredential team beneficial, but the hours were not used frequently or by all participants. One participant plainly stated, " . . . The office hours were really nice . . . " (participant Cohort 1), while others alluded to the fact that they were not used.

In the subtheme "resources used", the teachers referenced the videos, lesson plans, and flashcards most often. For the videos, teachers made comments such as, "The videos were where I took most of my information from, the short articles, [and] the websites" (participant Cohort 1). Another teacher said, "I felt like that [the videos] helped just solidify the understanding that I came to in the course" (participant Cohort 1). The videos were often referred to as better than other resources, such as, " . . . the technical material, I read it, but it wasn't as engaging to me as the video was" (participant Cohort 1). Another participant said, "I felt that there was a good variety of ways that the information was distributed, both in text and in video. So, the video choices were very good, I thought the video choices were excellent, actually" (participant Cohort 1). For the lesson plans, one teacher, stating what others summarized, said, "I love the ideas of lesson plans. I love the ideas of writing good, solid lesson plans. I think it has to be one of those things [where you can] choose to write [the lesson plan], maybe just with a list of please include the following things in your lesson plan" (participant Cohort 1). This trend continued in Cohort 2, as explained by one teacher: "it was nice that [the lesson plan] was something that you could actually, like, use in class" (participant Cohort 2). For the flashcards, one teacher, echoing what others also stated, said that the flashcards were "a nice, tactile thing that I could use to actually hold in my hands . . . I appreciate flashcards" (participant Cohort 1). Another teacher said, "I like flipping through flashcards [and learning the content]" (participant Cohort 1), while a third stated, "I had a basic knowledge, but now I have some actual, like, terminology that goes with it" (participant Cohort 3). Others thought that the flashcards were too traditional and an outdated teaching tool.

For the main theme "Implementation", the subthemes of "implementation in the classroom " and "implementation of the next microcredential" were discovered. For the subtheme "implementation in the classroom", the teacher participants expressed a desire for materials/resources that were ready to reuse without modification. One teacher commented, " . . . I like when things are directly applicable, because then I can just push them into my classroom . . . " (participant Cohort 1). Another teacher stated, "I especially liked the unplugged activities . . . it's always a good idea to have those types of things that bring it to such a concrete level to your students . . . I would suggest you add more of them in." One teacher "felt like [the microcredential] was really interesting, [not] cookie cutter, and what I could actually implement into my classroom" (participant Cohort 3). Regarding using the flashcards in the classroom, one teacher said, "I think that the most valuable [aspect] was that . . . the information from the flashcards, or even the flashcards themselves, . . . could be used in the classroom . . . " (participant Cohort 1). Other teachers pointed out that they needed more background information to create quality products for their classrooms. For example, one teacher said that the lesson plan that they created "didn't have many higher-level thinking skills [in it], but I didn't necessarily . . . have the content [knowledge to do that well at the time]" (participant Cohort 2). The majority of the teachers said something like, " . . . I always like things that I can, like, take and use specifically in my classroom" (participant Cohort 2). Some of those teachers went on, mentioning specific pieces that they would use in the classrooms, such as, "I especially liked the unplugged activities because I just think it's always a good idea to have those types of things that bring it to such a concrete level to your students" (participant Cohort 2).

In the "implementation of the next microcredential" subtheme, the teachers pointed to resource use, either ways to increase the use of what was offered or to add different resources. For example, one precollegiate teacher stated, "I would suggest maybe just [adding] some samples for teachers in the grade-band areas . . . you could say okay, if you are teaching K-2 this might be an appropriate activity, if you are teaching 6–8, if you picked a K-2 activity, this is how you would ramp it up . . . ". Another Cohort 1 teacher commented, "I think if there could be either videos or, like, an instructor presenting, I'm a really traditional, like, learner . . . you could do a video of yourself teaching the concept and taping it—just, like, [add] a short video".

Another set of teachers wanted to see more direct connections to STEM content. One of them summed this up when stating, "if you could find some of these ideas that tied into, like, a science class or math class, I would think that would be very helpful for teachers because, like, as a teacher you're always so worried about your own content, [and] it's hard to balance bringing [any] extra activities in [like cybersecurity content on its own]" (participant Cohort 2).

The teachers were forthcoming about what modules challenged them and what to improve. For example, "I just didn't know, like, a ton about the modularity [piece]. I had heard the word, but I gained a lot of knowledge on that. And I really struggled with the whole idea of abstraction, like, I get it, but I couldn't explain it. So, I had to go through a few things to . . . break it down [maybe you could assist with this]" (participant Cohort 2).

The qualitative findings showcase the continued interest in the teacher resources presented in the microcredential and how they could be used for classroom implementation.

As summarized in Figure 5, the "Resource" theme had marked areas for "resources offered" and "resources used", while the "Implementation" theme had the distinct subthemes of "implementation of the next microcredential" and "implementation in the classroom".

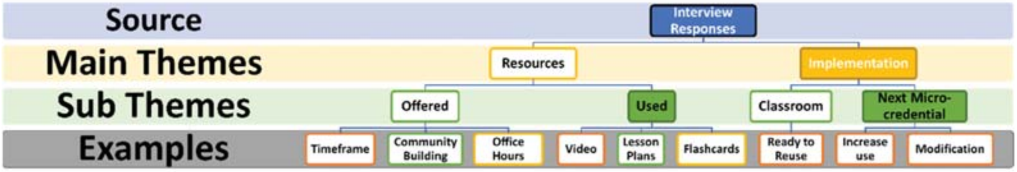


Figure 5. Representation of main themes and subthemes with examples.

6. Conclusions and Contributions to STEM Education

Overall, in relation to how the cybersecurity microcredential impacts precollegiate teachers' computer science self-efficacy (the first research question), the microcredential seemed to increase the teacher participants' self-efficacy regarding teaching all students computer science. The teachers also used concepts required by the CS curriculum. In the survey as well as the interviews, the teacher participants showcased their belief that they could teach cybersecurity concepts in their courses (both STEM and CS). Knowing that teachers gain confidence in teaching cybersecurity concepts after a shorter-duration microcredential is in line with the Dunning–Kruger effect [33], where people overestimate their knowledge and skill set, then struggle with the content/skills and with continued work find a place of actual use for the content/skills. Teachers taking the cybersecurity microcredential would most likely need support for the sustainable use of the content.

The second research question focused on the amount of time that precollegiate teachers spent in the microcredential, and the amount of time spent by any teacher varied drastically. There was a weak, positive relationship between the English/literacy teachers and the use of the microcredential resources for more overall time. The English/literacy group utilizing the resources for more time could speak to the potential need for English/literacy teachers to explore and understand a domain outside of their usual expertise. While high school educators might have spent more time with the resources because they were more relevant to classroom implementation, this was not explicitly asked or addressed. Conversely, STEM teachers were less likely to use the resources for long periods of time, and this could be related to teaching precollegiate students in the middle of their studies before college begins (as many of the STEM teachers taught at this level). Interestingly, these science and STEM teachers were more likely to have more overall self-reported biweekly hours (or total hours spent) but were shown to have less LMS/resource hours.

Regarding how the precollegiate teachers shaped the microcredential to be more effective (the third research question), the teachers focused on the resources and the implementation (for themselves and for their future students) to improve the microcredential. Additionally, as stated earlier, an online PD study (which is similar to a cybersecurity microcredential) showed that the areas in need of attention included matching PDs to the teachers' backgrounds, aligning the PD with curricula, and using motivational design to enhance teacher engagement [26]. The authors of this article agree with these areas of attention for PDs and add that a focus on the teacher resources should be offered with considerations for future classroom use as well as the implementation factors (for both the microcredential parts and for future students). These areas of attention are also warranted when creating microcredentials. In the three Cohorts, there were more female teachers participating (n = 22) than male teachers (n = 8), which follows the current overall teacher demographics; however, the situation is flipped in current precollegiate CS teacher trends, which are still dominated by males.

Since the participant teachers were either STEM or CS teachers, these findings can help guide those creating other microcredentials, PDs, or content resources. The authors argue that focusing on how to develop meaningful, specialized-content microcredentials for educators will only become more important. Notably, the intervention of a cybersecurity microcredential increased the self-efficacy of precollegiate teachers toward CS, as has been shown in other disciplines [21]. The results illustrate that resources such as sample lesson plans, activities such as flashcards, and mentoring in office hours impacted precollegiate teachers' self-efficacy toward CS, allowed them to create materials for future classroom use (or implementation), and gave them space to voice an opinion on what was or was not functioning to motivate them in engaging with the microcredential. Moreover, the identified resources and implementation pieces assisted the teachers in making the connections between cybersecurity and their disciplinary subject area, as explained in the interviews about future cybersecurity classroom lessons.

Although not part of this study, an informal follow-up email asked the participants about the classroom use of the lesson plans that they created during the microcredential. Based on the responses, at least 46% (14/30) self-reported that they used the cybersecurity lessons they created. Thus, after the microcredential, almost half of the precollegiate teachers (across a variety of disciplines) were able to introduce computer science/cybersecurity unplugged activities and lesson plans into instruction without using any specialized technological devices.

One of the study's successes was that the majority of the precollegiate teachers believed that they had an ability to teach the computer science and cybersecurity content in their classroom when they had resources provided, especially when they could be immediately used in the classroom. On the other hand, one of the main challenges was creating the right balance of resources to teacher activity for engagement, reflection, and potential classroom implementation. The teacher participants seemed to prefer shorter readings, videos, and go-to classroom resources.

Our recommendations for creating a computer science or cybersecurity microcredential include:

1. Follow prior recommendations in the literature for online PDs and microcredentials, such as matching PDs to teachers' backgrounds, aligning the PD with curricula, and using motivational design to enhance teacher engagement [20].
2. Focus on creating teacher resources that could be offered to a middle or high school STEM or CS classroom audience, so that the teachers have to make less modifications for use. This includes novice, intermediate, and advanced resources.
3. Use resources (such as journal articles and flashcards) that include sample computer-science- or cybersecurity-related unplugged and plugged activities, showing that computer science is more than coding and involves problem-solving. Use shorter readings and videos when possible.
4. Identify for the teachers where classroom implementation could be beneficial for students to make disciplinary connections in and beyond STEM.
5. Offer support to teachers for classroom implementation, beyond asynchronous support such as email. If traveling to the location is not feasible, then synchronous engagement offers a stronger assistance for sustainable use.

7. Limitations, Future Research, and Implications

The main limitation of this work is the number of teacher participants (n = 30) across the three Cohorts/Pilots. Additionally, since the purpose of the Pilots was to create a stronger cybersecurity microcredential, all three Pilots differed in some way, affecting the data collection consistency. Another limitation is a lack of previous research studies on microcredentials and, in particular, on the cybersecurity education field. Prior related research studies seem limited and need further data collection on developing, implementing, and evaluating high-quality microcredentials. The results of this study demonstrate that the cybersecurity self-efficacy increased, the time spent on microcredentials varied, and the teachers wanted to be able to use resources and then implement what was learned. Future research could focus on a more in-depth analysis of the teacher responses in both quantitative and qualitative measures. Additionally, as a future improvement, the team plans a final study that corroborates the modifications presented for success. Another question to explore is whether a microcredential can be tailored based on the demographic information of the participants. Since some precollegiate teachers used diagrams demonstrating computational thinking steps in their lesson plans (decomposition, abstraction, pattern recognition, algorithm design, evaluation, and logic) the connection between computer science, cybersecurity, and computational thinking might be another area ripe for exploration.

As the authors of this article believe that precollegiate teachers should utilize cybersecurity principles and concepts in their classroom (regardless of their subject area, background knowledge, or interest) the implications of this work extend to those creating microcredentials, PDs, teaching at any level, and involved in policy surrounding teaching certification and licensure. All stakeholders should be partners in creating microcredentials and resources, as they hold the key to influencing others to realize that computer science and cybersecurity go beyond coding, and that what the teachers need is an important aspect of what should be created for them.

Author Contributions: Conceptualization, B.M. and A.C.B.; methodology, B.M., M.B. and A.C.B.; LMS module, B.M.; validation, A.C.B. and M.B.; formal analysis, A.C.B. and M.B.; investigation, B.M. and A.C.B.; resources, B.M.; data curation, B.M.; writing—original draft preparation, B.M.; writing—review and editing, A.C.B. and M.B.; visualization, A.C.B. and M.B.; supervision, M.B.; project administration, B.M.; funding acquisition, A.C.B. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This material is based upon work supported by the Wyoming Department of Education (WDE) Micro-credential grant and in part by the National Science Foundation (NSF) under Grant No. SWARMS #1339853, WySLICE #1923542, WySTACK #2055621, and the National Security Agency (NSA) GenCyber #H98230-21-1-0129. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the WDE, NSF, or NSA.

Institutional Review Board Statement: The study was approved by the Institutional Review Board of the University of Wyoming (#20201218ABO2913 in Fall 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to IRB restrictions.

Acknowledgments: The authors would like to thank the teachers and student researchers that worked on this project as our partners. The students are Caitlin Person, Caitlin Kennedy, Amanda Carson, and Alex Finch.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Aefsky, F. COVID19 Pandemic Impact on Education in the United States. Interdisciplinary Insights. *J. St. Leo Univ. Coll. Educ. Soc. Serv.* **2021**, *3*, 3–13.
2. National Academies of Sciences, Engineering, and Medicine. *Reopening K-12 Schools during the COVID-19 Pandemic: Prioritizing Health, Equity, and Communities*; National Academy Press: Washington, DC, USA, 2020.
3. Black, E.; Ferdig, R.; Thompson, L.A. Pre-collegiate virtual schooling, COVID-19, and student success. *JAMA Pediatrics* **2021**, *175*, 119–120. [CrossRef] [PubMed]
4. Barnett, B.; Airhart, K.M.; Byrd, P.A. Microcredentials: Teacher learning transformed. *Phi Delta Kappan* **2016**, *98*, 34–40.
5. Bartz, D.E.; Kritsonis, W.A. Micro-Credentialing and the individualized professional development approach to learning for teachers. *Natl. Forum Teach. Educ. J.* **2019**, *29*, 1–11.
6. Brown, D. *Research and Educator Micro-Credentials*; Digital Promise; 2019; Available online: https://digitalpromise.dspacedirect.org/bitstream/handle/20.500.12265/46/Researcher-And-Educator-Microcredentials-2019.pdf?sequence=1 (accessed on 8 December 2021).
7. Lawless, C. Synchronous vs Asynchronous Learning: Which Is Right for Your Learners? *LearnUpon*. 2020, p. 23. Available online: https://www.learnupon.com/blog/synchronous-learning-asynchronous-learning/ (accessed on 8 December 2021).

8. Nieuwoudt, J.E. Investigating synchronous and asynchronous class attendance as predictors of academic success in online education. *Australas. J. Educ. Technol.* **2020**, *36*, 15–25. [CrossRef]
9. Burrows, A.C.; Borowczak, M.; Slater, T.F.; Haynes, C.J. Teaching computer science & engineering through robotics: Science & art form. *Probl. Educ. 21st Century* **2012**, *47*, 6–15.
10. Mugayitoglu, B.; Borowczak, M.; Burrows, A.C. A university's developmental framework: Creating, implementing, and evaluating a K-12 teacher cybersecurity microcredential course. *J. Syst. Cybern. Inform.* **2021**, *19*, 13–22, ISSN: 1690-4524.
11. Wing, J.M. Computational thinking. *Commun. ACM* **2006**, *49*, 33–35. [CrossRef]
12. Wolf, S.; Burrows, A.C.; Borowczak, M.; Johnson, M.; Cooley, R.; Mogensen, K. Integrated outreach: Increasing engagement in computer science and cybersecurity. *Educ. Sci.* **2020**, *10*, 353. [CrossRef]
13. Burrows, A.C.; Borowczak, M.; Myers, A.; Schwortz, A.C.; McKim, C. Integrated STEM for teacher professional learning and development: "I Need Time for Practice". *Educ. Sci.* **2021**, *11*, 21. [CrossRef]
14. Johnson, C.C.; Mohr-Schroeder, M.J.; Moore, T.J.; English, L.D. (Eds.) *Handbook of Research on STEM Education*; Routledge: London, UK, 2020.
15. Coyne, J.; Hollas, T.; Lane, M.; Ellis, C. Microcredentials: A Promising Professional Development Model for Teacher Leaders. *Int. J. Innov. Res. Educ. Sci.* **2019**, *6*, 647–654.
16. Borowczak, M.; Burrows, A.C. Ants go marching—Integrating computer science into teacher professional development with NetLogo. *Educ. Sci.* **2019**, *9*, 66. [CrossRef]
17. Bers, M.U. Coding as another language: A pedagogical approach for teaching computer science in early childhood. *J. Comput. Educ.* **2019**, *6*, 499–528. [CrossRef]
18. Saxena, A.; Lo, C.K.; Hew, K.F.; Wong, G.K.W. Designing unplugged and plugged activities to cultivate computational thinking: An exploratory study in early childhood education. *Asia-Pac. Educ. Res.* **2019**, *29*, 55–66. [CrossRef]
19. Sun, L.; Hu, L.; Zhou, D. Improving 7th graders' computational thinking skills through unplugged programming activities: A study on the influence of multiple factors. *Think. Ski. Creat.* **2021**, *42*, 100926. [CrossRef]
20. Gonzalez-Manzano, L.; de Fuentes, J.M. Design recommendations for online cybersecurity courses. *Comput. Secur.* **2019**, *80*, 238–256. [CrossRef]
21. Bhuyan, J.; Wu, F.; Thomas, C.; Koong, K.; Hur, J.W.; Wang, C. Aerial drone: An effective tool to teach information technology and cybersecurity through project based learning to minority high school students in the U.S. *TechTrends* **2020**, *64*, 899–910. [CrossRef] [PubMed]
22. Cavelty, M.D.; Wenger, A. Cyber security meets security politics: Complex technology, fragmented politics, and networked science. *Contemp. Secur. Policy* **2020**, *41*, 5–32. [CrossRef]
23. Kilty, T.; Burrows, A.C.; Welsh, K.; Kilty, K.; McBride, S.; Bergmaier, P. Transcending disciplines: Engaging college students in interdisciplinary research, integrated STEM, and partnerships. *J. Tech. Sci. Educ.* **2021**, *11*, 146–166. [CrossRef]
24. Lambert, J.; Cioc, C.; Cioc, S.; Sandt, D. Making connections: Evaluation of a professional development program for teachers focused on STEM integration. *J. STEM Teach. Educ.* **2018**, *53*, 2. [CrossRef]
25. Kelley, T.R.; Geoffery Knowles, J.; Holland, J.D.; Han, J. Increasing high school teachers self-efficacy for integrated STEM instruction through a collaborative community of practice. *Int. J. STEM Educ.* **2020**, *7*, 1–13. [CrossRef]
26. Qian, Y.; Hambrusch, S.; Yadav, A.; Gretter, S. Who needs what: Recommendations for designing effective online professional development for computer science teachers. *J. Res. Technol. Educ.* **2018**, *50*, 164–181. [CrossRef]
27. Chen, S.; Venkatesh, A. An investigation of how design-oriented organizations implement design thinking. *J. Mark. Manag.* **2013**, *29*, 1680–1700. [CrossRef]
28. Sweeney, L.B.; Meadows, D. *The Systems Thinking Playbook: Exercises to Stretch and Build Learning and Systems Thinking Capabilities*; Chelsea Green Publishing: White River Junction, VT, USA, 2010.
29. York, S.; Lavi, R.; Dori, Y.J.; Orgill, M. Applications of systems thinking in STEM education. *J. Chem. Ed.* **2019**, *14*, 2742–2751. [CrossRef]
30. Astaíza-Martínez, A.F.; Mazorco-Salas, J.E.; Castillo-Bohórquez, M.I. Teacher-researcher training in higher education: A systems thinking approach. *Syst. Pract. Action Res.* **2021**, *34*, 187–201. [CrossRef]
31. Patrick, S.; Worthen, M.; Frost, D.; Truong, N. *Current to Future State: Issues and Action Steps for State Policy to Support Personalized, Competency-Based Learning*; iNACOL: Vienna, VA, USA, 2018.
32. Ravitz, J.; Stephenson, C.; Parker, K.; Blazevski, J. Lessons from evaluation of computer science teacher professional development in Google's CS4HS program. *ACM Trans. Comput. Educ.* **2017**, *17*, 21. [CrossRef]
33. Kruger, J.; Dunning, D. Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. *J. Personal. Soc. Psychol.* **1999**, *77*, 1121–1134. [CrossRef]

education sciences

MDPI

Article

Beyond Content: The Role of STEM Disciplines, Real-World Problems, 21st Century Skills, and STEM Careers within Science Teachers' Conceptions of Integrated STEM Education

Emily Anna Dare [1,*], Khomson Keratithamkul [2], Benny Mart Hiwatig [2] and Feng Li [1]

[1] Department of Teaching and Learning, Florida International University, Miami, FL 33032, USA; fli003@fiu.edu
[2] Department of Curriculum and Instruction, University of Minnesota, Minneapolis, MN 55455, USA; kerat001@umn.edu (K.K.); hiwat001@umn.edu (B.M.H.)
* Correspondence: edare@fiu.edu

Citation: Dare, E.A.; Keratithamkul, K.; Hiwatig, B.M.; Li, F. Beyond Content: The Role of STEM Disciplines, Real-World Problems, 21st Century Skills, and STEM Careers within Science Teachers' Conceptions of Integrated STEM Education. *Educ. Sci.* **2021**, *11*, 737. https://doi.org/10.3390/educsci11110737

Academic Editors: Andrea Burrows and Mike Borowczak

Received: 11 October 2021
Accepted: 8 November 2021
Published: 16 November 2021

Abstract: Understanding teachers' conceptions surrounding integrated STEM education is vital to the successful implementation of integrated STEM curricula in K-12 classrooms. Of particular interest is understanding how teachers conceptualize the role of the STEM disciplines within their integrated STEM teaching. Further, despite knowing that content-agnostic characteristics of integrated STEM education are important, little is known about how teachers conceptualize the real-world problems, 21st century skills, and the promotion of STEM careers in their integrated STEM instruction. This study used an exploratory case study design to investigate conceptions of 19 K-12 science teachers after participating in an integrated STEM-focused professional development and implementing integrated STEM lessons into their classrooms. Our findings show that all teacher participants viewed STEM education from an integrative perspective that fosters the development of 21st century skills, using real-world problems to motivate students. Our findings also reveal that teachers have varying ideas related to the STEM disciplines within integrated STEM instruction, which could assist teacher educators in preparing high-quality professional development experiences. Findings related to real-world problems, 21st century skills, and STEM careers provide a window into how to best support teachers to include these characteristics into their teaching more explicitly.

Keywords: STEM education; professional development; qualitative; case study; teacher conceptions

1. Introduction

Over the past few decades, K-12 education has seen an increased focus on teaching science, technology, engineering, and mathematics (STEM) to prepare students to meet the needs of today's society. In some countries, this focus has been targeted towards an integrated approach to teaching the STEM disciplines, often referred to as integrated STEM education. In the United States, *A Framework for K-12 Science Education* [1] and the *Next Generation Science Standards* [2] explicitly call for the inclusion of engineering, along with mathematical and computational thinking as part of science and engineering practices, into K-12 science education. This inclusion of engineering and an awareness of the intimate relationship among STEM disciplines signifies a shift towards more application-oriented settings of science that provide relevant contexts inspired by real-world problems and an emphasis on developing 21st century skills [1], a set of skills that help individuals meet the needs of our increasingly technological society. This type of integrated STEM learning has the potential to increase students' interest and motivation in learning STEM concepts and practices, better positioning them to consider a future STEM career [3,4].

Unfortunately, research that attends to these concerns related to student outcomes may not be fruitful until the education community better understands the nature of STEM integration within K-12 classrooms. Adding to this complexity, there is a distinct lack of consensus surrounding how STEM is conceptualized among stakeholders [5–9], making it challenging for teachers to know what to do in their classrooms and for teacher educators to know how to support teachers' professional learning [10–12]. Although certain characteristics of STEM education are shared within the broader community, such as the need to include authentic real-world problems, help students develop 21st century skills, and promote STEM careers [1,13–15], others are less well-defined. For instance, although most of the literature agrees that at minimum, two disciplines should be present, determining the exact nature of integration has been a challenge, as there are "difference[s] in how scholars conceptualize the role of each discipline" [14] (p. 4). In short, there is still debate over how many disciplines are required in order to label instruction as "integrated STEM", and the presence, priority, and role of each discipline varies depending on who you ask [11,14]. Similarly, despite agreement about the need to include content-agnostic aspects such as real-world problems, 21st century skills, and STEM careers [9,10,13], there is a lack of research that explores how teachers conceptualize these components within their instruction. Although some, such as Bybee [7] and Breiner and colleagues [6] caution against having one definition for STEM education, there is a need to refine what it looks like in K-12 classrooms to help teacher educators better design professional learning opportunities to support those interested in implementing integrated STEM education.

Issues concerning the variety of conceptions surrounding the nature of STEM integration highlight the complexity of teachers' own conceptions of STEM and their implementation of such teaching practice. Because teachers' conceptions play a role in their teaching practice [16,17], there is much to learn about teachers' conceptions of integrated STEM to make sense of the instructional decisions they make in the classroom and to better support their work. As such, the purpose of this study is to examine teachers' conceptions related to specific components. As noted above, the literature agrees that multiple disciplines are required, but determining how teachers conceptualize the role of each discipline and the connections between them has yet to be explored in depth. Similarly, the literature agrees that real-world problems, 21st century skills, and promoting STEM careers are important for student learning in integrated STEM education, but it is unclear how these content-agnostic characteristics are conceptualized by teachers; prior research only points to teachers' acknowledgement that they are important to include [10]. Given the uncertainty surrounding conceptions of STEM integration related to these areas, this study sought to address the following research questions: (1) *How do teachers conceptualize the role of science, technology, engineering, and mathematics within integrated STEM education*? and (2) *In what ways do teachers conceptualize real-world problems, 21st century skills, and promotion of STEM career awareness within integrated STEM instruction?*

1.1. Literature Review

1.1.1. Teacher Conceptions of STEM Education

The lack of a clear definition of STEM education is unsurprisingly reflected in the abundance of K-12 teachers' conceptions of STEM education [9,11,12,18]. Although variations exist, we [5] found that science teachers preferred models that address the interconnection of STEM disciplines, are science-centric, and allow students to make connections between what they do in school and what happens in the "real-world". One common theme in K-12 spaces is that the term "STEM education" equates to "integrated STEM education" [5,18]. It is also clear that K-12 teachers recognize STEM education as more than teaching multiple disciplines simultaneously, even if pre- and in-service teachers struggle to articulate how many disciplines are needed [11] or neglect to describe how it should be enacted in the classroom [12]. These problems reflect those found across different definitions and conceptual frameworks for STEM [14].

Currently, professional development opportunities related to integrated STEM education are limited and include wide variations in how integrated STEM instruction is promoted [19]. However, the literature has noted the importance of professional development in helping teachers develop and refine their own conceptions of STEM education and transform their practice towards a more integrated approach [10,18,20–23]. Du and colleagues [21] noted the positive effect professional development had on teachers' perceptions of STEM education, which also made them aware of what support they needed for implementation. After participating in a year-long professional development experience, Wang and colleagues [24] found that teachers from different disciplines held various conceptions of STEM education, which was reflected in their practice. Similarly, we [10] found that after participating in professional development, teachers' conceptions of STEM education translated directly into their written curriculum. This included conceptions related to the degree of integration, such as connecting the disciplines, balancing science and engineering, and science- or engineering-focused. Although this work did not explore the role of each STEM discipline explicitly, these themes elucidate the fact that teachers make some decisions related to the role of each discipline. This is most prominently reflected in the finding that teachers often positioned mathematics and technology as tools/supports in STEM [10,18].

What is important to emphasize within these few studies examining teachers' conceptions of integrated STEM is that the shift towards some model of integrated STEM instruction goes beyond content integration. For example, in addition to the themes mentioned above, we [10] noted two content-agnostic aspects within their conceptions and written curriculum related to the importance of including 21st century skills and connections to the real-world. This emphasis on the inclusion of 21st century skills and connections to the real-world includes opportunities for students to learn about STEM careers [5,10]. It is these components of STEM education that allow teachers to focus on preparing their students for future success by arming them with the necessary skills [9]. However, in-depth exploration of these areas within integrated STEM teaching and learning has not been the focus of much research. Exploration in these areas is needed to better understand the needs of teachers and students as they engage in integrated STEM teaching and learning.

1.1.2. Beyond Content in Integrated STEM Education

The literature related to STEM education consistently includes several characteristics that differentiate integrated STEM from a more traditional teaching approach: real-world problems, 21st century skills, and STEM careers [1,14,15]. First, the use of real-world problems reflects the need to increase diversity in STEM fields [25,26]. Engaging students in developing solutions to real-world problems helps to motivate and contextualize learning [27], while also allowing students to draw from their knowledge of multiple STEM disciplines [28]. These problems should connect to students' lives to enhance engagement and increase the relevance of learning [29–31]. While the use of real-world problems is included in the literature as important, and previous research has noted teachers' awareness of this need [5,10], it is yet unknown how teachers approach this aspect in their conceptions and practice.

Second, one of the main goals of K-12 STEM education is to support learners' development of skills needed to succeed in their pursuit of STEM careers and in their adult lives [1,32,33]. These skills have been commonly referred to as 21st century skills, which are sought after by employer [4] and play an essential role in meeting the goals of integrated STEM education [33–36]. With rapid advancements in technology and globalization, future STEM professionals need to be adept in critical thinking and creativity to solve problems, be able to work productively in teams, and communicate effectively [33,37,38]. Communication, collaboration, creativity, and critical thinking (the 4-Cs) are deemed as core 21st century skills for higher education, the job market, and society in general [33] (Table 1). They are also seen as vital skills needed in innovation and design-focused environments [39]. The 4-Cs empower students to search, learn, and apply content knowledge to solve problems, which are crucial skills for young learners [40]. Despite agreement that these skills are pivotal for students' success, it is unclear how these skills fit into teachers' conceptions of integrated STEM education.

Table 1. Description of the 4-Cs.

4-Cs	Short Description
Critical Thinking	Critical thinking is the ability to look for evidence to support claims and beliefs [41] and ask and answer critical questions [42]. It encompasses effective reasoning, systems thinking, making judgments and decisions, and problem solving [39].
Creativity	Creativity is a multifaceted skill [43] that leads to innovation and effective problem solving. It comprises generation of multiple ideas and solutions to problems and making associations between remote concepts [44].
Collaboration	Collaboration is an essential skill in problem solving and the construction of knowledge. It is manifested when members communicate with each other, reflect as a group, make decisions collectively, build trust, manage conflicts, maximize collective knowledge, and take turns assuming leadership roles [45,46].
Communication	Communication comprises information delivery, interpersonal skills, interactive communication, and even teamwork, among others [47]. With the emergence of new technologies, communication becomes coupled with the increased use of information and communications technology (ICT) that allows learners to acquire information more efficiently, communicate faster and more effectively, and maximize learning, overall [48].

Finally, the inclusion of 21st century skills within integrated STEM education connects what happens during instruction to the types of practices and skills used by STEM professionals. This is one way to help introduce students to STEM careers and potentially increase diversity within STEM fields [1,37,49]. Since teachers play an important role in shaping students' perceptions of and introducing students to actual STEM professionals [50,51], introducing STEM careers can be done by making explicit connections to and promoting awareness of STEM careers. This can empower students to pursue careers in STEM and fill the increasing societal need for STEM workers [1], especially in terms of increasing historically marginalized students' engagement and interests in STEM [26,52–54]. Integrated STEM education, then, can be a means for historically underrepresented students in STEM to push back against social injustices. However, little is known about how teachers conceptualize or accomplish this in their integrated STEM teaching. Some note that this may be challenging for teachers who have little knowledge of STEM careers [55], and that they could benefit from professional development that includes STEM professionals as guest speakers [56].

Because little is known about the specifics of teachers' conceptions of integrated STEM education with respect to areas such as real-world problems, 21st century skills, and STEM career awareness, there is a need to conduct research in this area. It is clear that these components are valuable to teachers [5,10], but better understanding how they frame these components in the broader context of their conceptions of integrated STEM education may help teacher educators better support them in their professional learning. What is clear is that teaching integrated STEM is more than just teaching multiple disciplines, but research related to teachers' conceptions must go beyond counting disciplines to better examine the nature of disciplinary relationships and exploring critical content-agnostic characteristics of integrated STEM education.

2. Materials and Methods

2.1. Research Design

This study utilizes an exploratory case study design [57,58] to explore teachers' conceptions of integrated STEM education, focusing on the role of each STEM discipline and how real-world problems, 21st century skills, and STEM careers fit into their conceptions of STEM education. This choice of design reflects the need to study a phenomenon that is underexplored [57,58]. As noted above, there are limitations in the research community's understanding of the role of STEM disciplines within conceptions of STEM education. To our knowledge, none of the studies have attended in detail to the specifics of conceptions of each STEM discipline and other aspects of integrated STEM education that go beyond an examination of disciplinary content.

2.2. Conceptual Framework

The work presented here was conducted as part of a larger project that required the development of a new conceptual framework for integrated STEM education. It focuses on practical characteristics to be included as part of K-12 integrated STEM curricula and practice [13]. We initially drew from the broad definition provided by Kelley and Knowles [59] wherein STEM education is "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" (p. 3). We expand upon this definition to include seven central characteristics that should be incorporated as part of K-12 integrated STEM curricula and practice: (1) engineering design, (2) real-world problems, (3) context integration, (4) content integration, (5) authentic STEM practices, (6) 21st century skills, and (7) STEM career awareness [13]. This particular conceptual framework is grounded in the notion that integrated STEM education is more than presenting students with content from multiple disciplines. Rather, it presents such content in a way that authentically represents the work of STEM professionals. Of particular importance is the emphasis on engineering design, which is contextualized by a real-world problem and engages students in the use of authentic STEM practices and 21st century skills. Above all else, this framework of integrated STEM is geared towards the inclusion of a diverse group of students and calls for explicit connections to both students' lives and STEM careers.

2.3. Study Context and Participants

The boundary of this case study is three 1-week professional development (PD) workshops focused on integrated STEM education offered to K-12 science teachers [60]; one of these workshops took place in an urban Southeast region of the United States and the other two workshops took place at the same site in the Midwest (separated by elementary and secondary teachers). These workshops provided teachers with a foundational knowledge of integrated STEM education as defined by our conceptual framework [13], examples of integrated STEM activities, lessons, and units, and dedicated time to modify or develop their own curriculum materials for classroom use. All workshops included a series of activities to elicit and support the development of teachers' conceptions of integrated STEM education [60]. On the first day, teachers sketched out their conceptions of STEM education, which provided a visual tool from which they could work; this visual was meant to encourage reflection of teachers' conceptions of STEM, including opportunities to refine their conceptions. While the full details of these activities can be found in [60], Table 2 provides a summary.

It is important to note that a prescriptive set of guidelines related to integrated STEM education was not shared with the teachers to encourage them to develop their own understanding that would work within their school context. This is especially important given that "PD programs have the best chance of impact on teacher and student outcomes when the goals of the PD program are aligned with policies at the school, district, and state levels, as well as existing teacher beliefs regarding STEM" [22] (p. 204). Rather than sharing a strict set of guidelines or a step-by-step recipe for implementing integrated STEM education, we presented integrated STEM education as four categories with a total of 13 elements (see Figure 1). These elements arose out of the conceptual framework [13], but it should be noted that one category (STEM pedagogies) was viewed as separate from the conceptual framework as it focused on quality of good teaching practice. Each of the sample integrated STEM activities was designed to highlight one or more of these elements. After teachers completed an activity as a student would, they engaged in prompted reflective discussions related to the targeted elements. The purpose of these discussions was to help teachers better understand and internalize these elements for inclusion in their own curriculum materials they were working on. After participating in the workshops, teachers were expected to implement their own lessons or lessons shared in the PD in their classrooms the following school year, during which a member of the project team observed and video-recorded the lesson(s).

Table 2. Summary of professional development workshop activities related to eliciting teachers' conceptions of STEM education [60].

Day 1: Eliciting STEM Conceptions	All teachers were asked to draw a model of STEM education that best represents how they currently understand STEM education.
Day 1: Sharing STEM Conceptions	Teachers met in small teams to discuss their models and then met as a large group to discuss if they would make changes to their model based on what they saw.
Day 1: The Role of S, T, E, and M	Teachers worked in small teams to consider the role of science, technology, engineering, and mathematics, using small sticky notes to describe the role of each in integrated STEM. These small sticky notes were then placed on large poster paper corresponding to each discipline and grouped by the teachers.
Day 5: Revisiting Eliciting STEM Conceptions	Similar to Day 1, all teachers were asked to draw a model of STEM education that best represents their current understanding of STEM education.

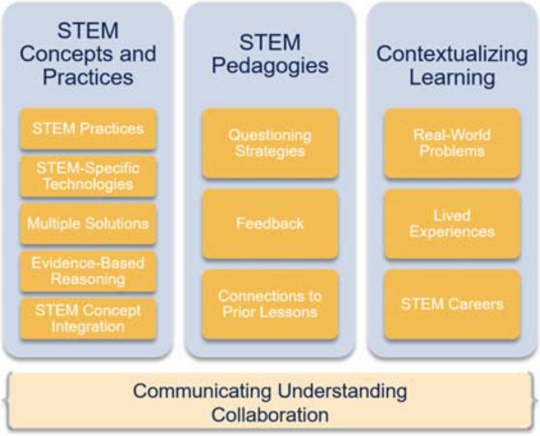


Figure 1. Visual map of integrated STEM education used in professional development [60].

A total of 106 elementary, middle, and high school teachers participated in the three workshops. Although interviews were planned with all teachers as part of their participation in the overall project, the abrupt shift to remote teaching as a result of the COVID-19 pandemic hindered our ability to interview all participants. Instead, teachers were recruited to participate via email requests sent out by the research team. This resulted in 17 secondary science teachers (10 high school and seven middle school) and two general elementary teachers agreeing to participate in interviews (Table 3). All participants modified or designed their own integrated STEM lesson(s) and had implemented at least one integrated STEM lesson in the 2019–2020 academic year prior to US schools transitioning to remote teaching.

Table 3. Teacher participants.

Site	Grade Band	Teacher Names (Pseudonyms)
Site 1	High School	Antonio (Physics), Christine (Biology), Jason (Marine biology, Physical science), Jocelyn (Biology), Liliana (Chemistry)
	Middle School	Clara, Darma, Edith, Pablo, Rose (all general science)
Site 2	High School	John (Physics), Elijah (Chemistry), Kyle (Physical science), Stacey (Environmental science), Tim (Physical science)
	Middle School	Alina, Mike (all general science)
	Elementary	Macy (3rd–5th grade), Marianna (5th grade) (all general elementary)

2.4. Data Collection and Analysis

Each interview took place via video conferencing, was recorded, and typically lasted 45–60 min. Prior to their interview, participants were asked to draw their current conception of STEM education and email it to the interviewer ahead of time. The purposes were to “prime” the teachers for the interview and to provide the interviewer with a point of reference. The interview protocol was organized to elicit teachers’ conceptions surrounding integrated STEM education as a whole, the role or purpose of each STEM discipline within integrated STEM education, how real-world problems fit into in their conceptions, how 21st century skills were included in their conceptions and teaching, and how teachers conceptualized promoting STEM career awareness in their classrooms. These interviews were not designed to measure the effect or impact of the PD on teachers, but rather to explore teachers’ conceptions after having implemented one or more integrated STEM lessons in their classrooms.

All interviews were transcribed verbatim prior to coding and analysis. The four-member research team first selected one transcribed interview to create a list of provisional codes as part of preliminary analysis [61]. Coding focused on teachers’ overall conception of STEM education, the role of each STEM discipline, the inclusion of real-world problems, the role of 21st century skills, and the promotion of STEM career awareness. After individually coding this selected interview and discussing codes as a group, the team refined the utilized codes and created a codebook. With a second pass through the same interview, all researchers used the codebook to recode the transcript. After a second discussion in which consensus was reached on codes and code placements, the codes were refined before coding additional transcripts. Each researcher coded all transcripts, adding additional codes as needed. Credibility and confirmability of these codes were established through coming to consensus through discussion. Once all transcripts had been coded and discussed, we grouped and organized the codes in a table to facilitate collapsing of the codes where similar codes overlapped. This visual display of codes allowed us to identify patterns across the interviews using thematic analysis [62]. This helped us focus on key features that aligned with our research questions. In looking across these patterns, we identified themes across our pre-selected categories (i.e., the research questions) that were common across teachers’ shared conceptions, which are described in the findings below.

3. Results

3.1. Overall Conception of Integrated STEM Education

We first examined teachers' overall conceptions of integrated STEM education to assess if this group of teachers' conceptions aligned to what previous research has found. In doing so, we identified five major themes: interconnection between disciplines, student-centered pedagogy, development of 21st century skills, STEM for all, and relevant and based in the real-world. These themes are described in Table 4, alongside sample quotes from teacher participants, and were determined to be consistent with the literature [5,10,14,18]. This initial analysis helped us to confirm that, in general, teachers' overall conceptions of STEM were consistent with previous findings, but our focused work dug deeper into the various elements of integrated STEM education.

Table 4. Summary of overall conceptions of integrated STEM education.

Theme	Brief Description	Example Quote
Interconnection between disciplines	An interconnection between STEM disciplines wherein the number of STEM disciplines are fluid and dynamic. When multiple disciplines are present, they should be connected in some way.	"kind of like a circle where we're going to be including all of this [STEM] all of the time or portions of this [STEM] some of the time". (Clara)
Student-centered pedagogy	Includes hand-on activities that could resemble project-based learning, which engages and excites students to learn STEM content.	"It's a way to implement steps you take, you know...some science and engineering. And then you come up with a project based on that. Or you take some math and you take some technology and you make a project based on that". (Mike)
Development of important skills	Integrated STEM education is a vehicle by which students could develop important skills in preparation for future success. These skills transcend different disciplines, including non-STEM disciplines.	"a good, strong, integrated STEM unit would be developing those, those skills, those life skills, um, for students, um, whether or not they go into the STEM field or not". (Stacy)
STEM for all	Integrated STEM should encourage and improve minoritized students' access to integrated STEM, including those from underrepresented racial and ethnic groups, women, and students with cognitive disabilities.	"You want to make sure that they are inclusive to all our learning disabled, our English language learners, our gifted". (Clara)
Relevant and based in the real-world	Integrated STEM education should utilize relevant and real-word problems that students can relate to. This should also allow students to connect between what they do in school with what STEM professionals do.	"You need to be more purposeful when you're designing what you're doing to make it, that the kids are actually doing the things that they do in STEM and being scientists and engineers". (Kyle) "That is the most important thing, is that solving problems that is relevant to real world issues". (Elijah)

3.2. Conceptualizing the Role of S, T, E, and M in Integrated STEM Education

We specifically asked teachers about the role of each STEM discipline within their conception of integrated STEM education, allowing them an opportunity to expand upon their overall conceptions. The sections below attend to this, summarized in Table 5. Included in these findings is our interpretation of how teachers positioned each discipline in relation to the others.

Table 5. Summary of themes describing the role of each STEM discipline.

Discipline	Themes
Science	• Epistemological construct • A central feature in STEM • Relationship of science to other STEM disciplines
Technology	• Tools to engage in STEM • Digital tools • A product of engineering • Relationship of technology to other STEM disciplines
Engineering	• Design-focused • Solving problems • Relationship of engineering to other STEM disciplines
Mathematics	• Tools and practices • Epistemological construct • Relationship of mathematics to other STEM disciplines

3.2.1. The Role of Science in Integrated STEM Education

Teacher's conceptions of science within integrated STME education focused on: (1) science as an epistemological construct and (2) science as central.

Epistemological Construct

Teacher participants described science as a body of knowledge to understand the world, a means to explore natural phenomena, or a discipline devoid of human input. For instance, Kyle mentioned that in science "we study the natural world, try to figure out how things work out there, have questions, do experiments to answer", supporting the idea that science is a means to explore natural phenomena through asking questions and conducting experiments. Stacy further noted, "...science being kind of the, the knowledge, the understanding of how the world works". This role of science as a body of knowledge and a way to learn about the world reflects positivist notions that science has correct answers.

A Central Feature in STEM

Teachers also described science as central to integrated STEM education and that without it, integrated STEM education would not exist. Subsequently, several teachers noted how science standards were the driver for STEM curricula. For instance, Kyle noted, "The science we learn—engineers can use those concepts into what they're making, designing, building, problem solving". Similarly, Stacy described how her integrated STEM unit planning begins with science before finding an appropriate engineering design challenge, centralizing the role of scientific content. Kyle even highlighted the importance of science beyond simply pursuing a science-related career, stating, "science opens lots of doors out there in the world". It is clear that teachers prioritized science in their understanding of integrated STEM education, which is not surprising given their position as science teachers.

Relationship of Science to Other STEM Disciplines

Teachers' positioning of science as their "starting place" when conceptualizing integrated STEM education reflects previous findings [10,19]. As science teachers, their perceived responsibility was in assuring that content was learned and standards were met. Beyond this, teachers noted the process of scientific discovery to understand the natural world, and suggests that that knowledge gained could be used by engineers to solve problems. In this vein, it appears that teachers readily saw connections between science and engineering, with only one teacher (Darma) commenting on the inseparable nature of science and mathematics.

3.2.2. The Role of Technology in STEM Education

Teacher participants described technology's role in STEM education in multiple ways. While not mutually exclusive, we identified three themes: (1) technology as tools to engage in STEM, (2) technology as digital tools, and (3) technology as a product of engineering.

Tools to Engage in STEM

Technology was most commonly discussed by teachers as a tool used to "do STEM" (i.e., tools used by students to complete tasks) or to teach STEM (i.e., tools for pedagogy). Some teachers considered technology as tools and equipment to facilitate engagement in STEM practices such as data collection, representation, and analysis, affording students the ability to engage in STEM learning by engaging in (or "doing") STEM practices. Stacy mentioned probeware (e.g., Vernier equipment) as an example of technology used in monitoring water in one of her STEM activities, noting "technology—I see as the tools, the things that we use, um, hopefully to make our lives a little bit easier". Teachers also described technology as tools for pedagogy, often as a means of communication among students. For instance, Allina saw technology as tools that "make it easier to share data. It [technology] makes it easier to analyze data. It [technology] makes it easier to collaborate". Further, Liliana emoted the complexity of technology, "a technology is not only for the presentation of the research. They [students] can also use it to create things, they can actually try to find ways to solve problems and create things with technology tools that they have available". The duality of engaging students either through their direct use of technology or through the teacher's pedagogical choices was seen as positive in nature as it facilitated students' accomplishment of tasks, which could not be done without the technology.

Digital Tools

In describing technology, more than half (11 out of 19) of the teachers described technology only in digital forms. In particular, Clara talked about her use of iPads to present course material, but also as a tool for students to develop and present their engineering designs. Likewise, Jocelyn mentioned digital spreadsheets as an example of technology that students used to organize and analyze data. While acknowledging the benefits of technology, teachers such as Jocelyn, Clara, Pablo, and Mike pointed out negative effects, with Mike stating, "I think there's a big danger in that it could be a distraction. You've got technology for technology's sake, it's not really helping anybody, but it sure looks cool". This focus on digital technology was sometimes viewed as a negative factor when it came to student learning. For example, Clara mentioned students being overly reliant on online tools to search for answers to problems, preventing students from exploring the questions and solving problems by themselves. She mentioned that "this quick access of getting answers [via technology] has caused them to be a little lazy". Some tension about the use of digital technology appears to exist within teachers' conceptions

A Product of Engineering

Five teachers explicitly described technology as the product of engineering, noting the connection between what is done within the engineering field and the tools that students use in class. Stacy noted, "That line between technology and engineering is very fuzzy because you're engineering a new technology". She expanded this by noting, "You know, scientists need a new technology to be able to find a new way to measure something or they need to invent something so that they can measure it". This can be thought of as a cyclical understanding of technology such that there are multiple access points for technology usage in the classroom.

Relationship of Technology to Other STEM Disciplines

Even though most teachers described technology as tools to engage in STEM learning, this could not be fully separated from the idea that technology is something akin to the binding agent between the other disciplines. This is made clear by Mike who shared, “so the technology piece is a little bit of the glue that brings a lot of those...have the science, the engineering, and the math together”. Rose also considered technology as the “key” to STEM toward creating “more effective solutions” to engineering problems. Stacy’s comments above about technology being a product of engineering demonstrates her belief that technology is an inherent part of science and engineering; further, this relationship is bidirectional. Although mathematics was not called out directly, teachers noted the importance of technology in performing tasks such as organizing and analyzing data.

3.2.3. The Role of Engineering in STEM Education

Teachers’ views of engineering within STEM education spanned two broad themes, which were not mutually exclusive from one another: (1) design-focused and (2) solving problems.

Design-Focused

All but five teachers focused their conceptions of engineering on the engineering design process. They described engineering as a cyclical, iterative design process used in the development of products or solutions to real-world problems or design challenges. According to Clara, this included “re-visiting original designs, fine-tuning them, going back, testing, and then making adjustments accordingly”. For Jason, engineering is “the process that they [students] have to use when they’re performing the tasks with the plan, design, model, test, evaluate, redesign, so forth”. Teachers such as Antonio noted the similarity between the scientific method and engineering, “It’s like a basic scientific method. All the steps. If you decide it’s not effective, you have to redesign it and that’s it—that is the way to do it”. Within this focus on the design process, teachers were conscious of including evaluation and redesign.

Solving Problems

In addition to the focus on the steps of the engineering design process, teachers described engineering as a context or vehicle to solve problems or develop products; this included general problem solving and solving contextualized, real-world problems. For instance, Kyle noted, “I think what engineers do is more of a problem solving-like, you’re given, ‘I need to accomplish this. How can we do it?’” Marianne noted that her students “understood the difference between the scientific method and the purpose of that—to answer questions... and engineering to come up with something to solve a problem”. Macy also noted the connection between designing and problem solving where her students “look at designs, improve designs, and use what they have already learned and what they know from previous experiences to improve or be able to solve their problems better”.

Relationship of Engineering to Other STEM Disciplines

The relationship between engineering and other STEM disciplines appeared to vary across teacher participants. Some conceptualized the role of engineering as both the creation of technology and application of scientific knowledge; for example, “engineers invent technology to do science” (Stacy) and that the “engineering design process goes hand in hand with science” (Clara). Engineering was also described as the integrator to provide a context to learn STEM content through a real-world problem, a theme that cuts across the previously mentioned themes related to engineering. Three biology teachers (Jason, Christine, and Jocelyn) noted the importance of engineering in integrated STEM education, but noted the challenges within biology courses due to cost and time. This relationship between engineering and the other disciplines was made the clearest with respect to science and technology; notably the connection to mathematics was not vocalized.

3.2.4. The Role of Mathematics in STEM Education

When asked to describe the role of mathematics within integrated STEM education, teachers' responses covered two related themes: (1) mathematics as tools and practices and (2) mathematics as an epistemological construct.

Tools and Practices

Similar to technology, mathematics was typically viewed as a set of tools or practices used to "do STEM". An overwhelming fourteen teachers viewed mathematics as a set of practices related to data analysis to answer scientific questions and/or to test engineering designs. Stacy noted how mathematics allows scientists to do their work, stating, "Newton's a perfect example of how the math and the science came together to be able to describe the world and how objects move with gravity. He needed to invent calculus to better describe mathematically his scientific principles". Mathematics as data analysis was described by Tim as, "you know math and data analysis and graphing and making decisions based on data is essential to STEM". Eleven teachers described mathematics as a set of tools. Liliana explained, "You need math for every calculation. So they need math for the formulas, they need math for the experiments". Jocelyn described how she and her students used math "to ultimately perform the engineering" through "working on statistics" using spreadsheets. She also related how her students "get the conceptual idea in their math class, but in the science world they're actually learning how to put formulas into spreadsheets or how to use math to describe populations and using math as a tool to describe patterns". As part of this, mathematics was described as data representational tools mostly through data graphing and visualization. Rose shared how, in her lessons, "the math part was the graphs, interpreting the graphs". It is clear that mathematics plays a vital role in integrated STEM instruction, especially when it comes to data analysis.

Epistemological Construct

Six teachers viewed mathematics as a body of knowledge within STEM education and provided examples of mathematics content knowledge used in their integrated STEM lessons, moving away from a vision of mathematics as primarily data analysis. For example, Rose described how she taught students to use the concept of ratio in their budget calculation for an integrated STEM project. As alluded to above, teachers also viewed mathematics as essential to integrated STEM, especially with respect to science, as students needed to be math literate. Simultaneous to with this, five teachers viewed mathematics as a barrier such that they viewed their students as lacking necessary mathematics knowledge and skills to solve problems. They described the mathematics within their STEM curricula as the basic knowledge and skills that every student should have, but were lacking. Pablo shared, "I think that the students don't have the background that they need to understand how to present data when they collect data in an experiment," which caused anxiety for him to implement integrated STEM lessons in his classroom. Tim pointed out that his students "don't even have the skills to do some of the stuff that we do on a regular basis with calculations".

Relationship of Mathematics to Other STEM Disciplines

In considering teachers' responses about the different ways in which mathematics can be used within integrated STEM education, the relationship is quite unclear. However, ten teachers noted how mathematics was central to STEM with Darma noting the critical connection between mathematics and science, "so without math, you can't do science". To some, mathematics was more of a supporting feature—used as tools or a set of practices (e.g., data analysis)—and it was seen by fewer teachers to be an isolated body of knowledge or central to STEM. Similar to technology, mathematics appears to be an area of STEM education that is not well-defined for science teachers; however, it should be noted that while the importance of mathematics was clear, its purpose varied.

3.3. Conceptualizing STEM beyond Content Integration

In addition to understanding how each STEM discipline is conceptualized within integrated STEM education, we further explored how teachers conceptualized and approached some of the content-agnostic aspects of integrated STEM education—real-world problems, 21st century skills, and promotion of STEM career awareness. By examining these areas, our hope was to better understand how science teachers shift from teaching science to teaching integrated STEM. Table 6 provides an overview of the final themes in each of these areas.

Table 6. Summary of themes describing real-world problems, 21st century skills, and promoting STEM career awareness.

Aspect of STEM	Themes
Real-World Problems	• Real-world problem as context • Relevance of the real-world problem
21st Century Skills	• 21st century skills are a pedagogical choice • 21st century skills need to be developed • 21st century skills relate to technology
Promoting STEM Career Awareness	• Promotion of STEM careers through curricula • Promotion of STEM careers through partnerships • Diversity-oriented promotion of STEM careers

3.3.1. Real-World Problems

Interviews revealed two main themes related to the use of real-world problems within integrated STEM education: (1) real-world problems as context and (2) relevance of the real-world problems. Three teachers noted that they faced challenges in incorporating or choosing appropriate real-world problems into their teaching with one teacher (Rose) noting the importance of needing a partnership to realistically include a real-world problem.

3.3.2. Real-World Problems as Context

Nine teachers described how they used real-world problems as a context for their integrated STEM instruction, which, according to Stacy and Allina, could foster long-term learning and deeper understanding of a given topic. Stacy noted, “I think that that comes right at the beginning with the teacher being explicit about “here’s a real-world problem that we need to work with”. Rose described how her integrated STEM lessons were grounded in real-world problems, describing an activity that involved creating unobtrusive weather stations. In particular, she noted the importance of partnerships to boost the authenticity of the problems, sharing “I believe that partnerships are incredibly important if you’re really going to teach the kids to tackle real life problems”.

3.3.3. Relevance of the Real-World Problem

In some cases, there was an overlap with using a real-world problem as a context for learning, but in other cases, teachers referred to general problems that were relevant to students. For Marianne, she believed that “if you create those real-world experiences, that creates the relevance. That creates the excitement. That creates the empowerment”. This was done either by selecting real-world problems directly related to students’ lives or to global issues. For example, Edith noted how she wanted her students to make a connection to their local environment for an integrated STEM unit related to recycling, “We took them in the context of the real world. I mean, we live in [our state]. We’re surrounded by water. There’re lakes. There’s the canal. There’s the Gulf and there’s the Atlantic”. Christine described how she connects her biology work with plants to measuring students’ carbon footprint, making strong connections to issues of global climate change. One particular example that shows this overlap was described by Darma, who discussed a way to bring the current COVID-19 pandemic into play, having her students explore viruses and materials to design and create facemasks. Conceptualizing real-world problems in these relevant ways appeared to motivate these teachers to bring integrated STEM to their students.

3.3.4. 21st Century Skills

In their overall conceptions, teacher participants described integrated STEM education as a way to help students develop skills for their current and future lives, but these skills were not described in detail until explicitly asked. Within teachers' responses related to 21st century skills, we identified three themes: (1) 21st century skills are a pedagogical choice, (2) 21st century skills need to be developed, and (3) 21st century skills relate to technology.

3.3.5. 21st Century Skills Are a Pedagogical Choice

Teacher participants viewed 21st century skills as part of their pedagogical choices. This centered primarily on the use of collaborative student groups, while some teachers also incorporated communication. Collaboration and communication were seen as necessary to enhance their use of integrated STEM education such that teachers required students to work in groups and used a variety of tools to encourage student communication of ideas. Elijah described, "We have to monitor and make sure that everybody's input is considered and make sure that everybody is participating". For communication, teachers also required their students to share their learning with others, often through technological affordances (e.g., PowerPoint, Excel). In some cases, such as Jason, communication was expected as an end product. He highlighted how "they [students] also communicate at the end–usually some type of presentation to your classmates". In this sense, both collaboration and communication were viewed as outcomes within a broader conception of integrated STEM education.

3.3.6. 21st Century Skills Need to Be Developed

Most teacher participants (17 out of 19) additionally noted the 4 Cs as a set of skills that K-12 students need to develop, and they were described as incorporated into typical classroom practice. This was done to provide students with, "tools or skills that they will be able to use not only in high school, but in their future" (Pablo). Although the general consensus was that these 4 Cs need to be developed, each skill was attended to in different ways. Collaboration was commonly noted as a set of skills that could and should be taught explicitly in classrooms. As Stacy noted, "collaboration just doesn't come naturally in a classroom. It needs to be explicitly taught, so much so that I actually have a rubric on teamwork". Teachers also described collaboration as a means to provide students with different perspectives, noting various benefits to working in small groups. Lilliana shared: "Collaboration is extremely important because they [students] learned that when they try to do things by themselves, sometimes they don't find a solution that they want, but when they work together, someone can come up with a different idea, come up with a different approach, and then they can just try to put this together".

Similar to the theme above, developing communication skills in the classroom was often intertwined with collaboration; oddly, those who described communication as pedagogy did not also describe it as a set of skills that need to be developed. Nonetheless, teachers recognized the importance of developing communication skills, citing their observations of miscommunications between students in a group during an integrated STEM lesson. Rose explained: "I remember having a group who had a hard time communicating and you could see it at the end and their prototype. They were fighting over, 'Yo, I want to use this material', 'No, this is better', 'No, this is better'... And again, they were wasting their time because they did not know how to communicate. So that is extremely important".

Rose went on to describe how some students communicate better with different modes of communication (e.g., email versus oral skills). Curiously, when describing the need for communication when students work in groups, teachers only provided examples of failed communication and did not note what successful communication would look like in their classrooms. These communication skills were also described in the context of STEM professionals with Allina describing how engineering is not just about an end product, but rather about sharing information with others.

Creativity was also described as a set of general skills, but teachers additionally highlighted the importance of creativity in solving problems in particular and as important for future careers in STEM fields and beyond. Twelve teachers described creativity as developing multiple ways to solve problems, which would help students think divergently. Antonio noted, “They have to create their own steps and I don’t like to give you steps. They have to be creative. They have to innovate. They have to design”. Macy described, “When I was teaching STEM, and really any subject area, I really tried to activate my students’ creativity and allow them to come up with their own ideas and build and solve problems using their imagination”. Four teachers addressed the importance of creativity in career aspects in particular. They viewed developing creativity for future careers as one of the purposes of integrated STEM education, even for students not pursuing a STEM career. Allina noted that “in order to be a productive part of whatever they do in society—whatever job—they have to be able to innovate”.

Of the 4-Cs, developing critical thinking skills was addressed to a lesser extent, although when it was mentioned, teachers related it to problem solving. For example, Mike noted, “I see lots of natural alignments between STEM and critical thinking. It’s not just learning so that you can become faster at information and processes. It’s more about, you know, we need people to solve problems”. This clear, explicit connection that Mike shared addresses how critical thinking is a part of problem solving within integrated STEM education. Six other teachers acknowledged the importance of developing critical thinking skills, but did not provide examples of how this was done in their classrooms.

3.3.7. 21st Century Skills Relate to Technology

As noted above, teachers often related technology with students’ ability to communicate with others, especially as a physical, digital tool (e.g., tablet, laptop). In addition to connections to the 4-Cs as part of 21st century skills, teachers also described other skills beneficial to students, such as technology literacy and digital technological skills (e.g., data analysis and computer programming skills). Teachers were clearly aware of the growing reliance on technology that students would need for their futures, independent of career choice. Teachers such as Clara noted, “We want to make sure that these students are prepared for the 21st century, that they are getting coding—that they’re getting the robotics, that they’re getting the engineering design principles”.

3.3.8. Promoting STEM Career Awareness

We identified three themes related to how teachers promoted STEM career awareness in their classrooms: (1) promotion of STEM careers through curricula, (2) promotion of STEM careers through partnerships, and (3) diversity-oriented promotion of STEM careers. These three methods of raising STEM career awareness were not mutually exclusive, but often overlapped with one another.

3.3.9. Promotion of STEM Careers through Curricula

Eleven teachers explicitly described their implementation of integrated STEM education as a vehicle to promote students’ STEM career awareness, with Antonio firmly establishing, “I think the main purpose of STEM education [is to] provoke students’ interest to participate in STEM careers”. Seven teachers also sparked students’ awareness of STEM careers by explicitly sharing that the practices they engaged in during class simulated authentic STEM practices used by STEM practitioners. Teachers such as Allina, Jocelyn, and Rose talked about the benefits of using real, scientific data, allowing students to better see and understand what STEM professionals do. Rose noted, "we have to start teaching the kids how the real-world is out there because they graduate and they know nothing". Additionally, five teachers described how they incorporated STEM careers into their STEM lessons to provide context and meaning to student learning. For example, Stacy mentioned that she talked about a specific STEM career during the introduction to one of her STEM lessons, noting the connection between the career and the topic of study.

3.3.10. Promotion of STEM Careers through Partnerships

Ten teacher participants described events such as inviting guest speakers to their classrooms and/or establishing partnerships with organizations, universities, and companies. Clara mentioned a partnership with a local university, which she leveraged to invite college students to speak to her middle school students, who she felt they would relate to better, "And so when a college student is telling a middle school student, 'Hey, you're going to need this, you know, this is going to help you,' they kind of pay attention a little bit more". Allina noted that her students were engaged in the authentic practices of STEM professionals via partnerships, which opened a new world to students about what they could do in STEM careers. She shared, "And it's like, I think it's really important for kids to see not just, okay, we're in class with this person, and they're saying this is cool. It's like, here's the newest stuff that people are doing". Having real STEM professionals talk to students helped teachers such as Allina showcase different STEM careers in an authentic and meaningful way.

3.3.11. Diversity-Oriented Promotion of STEM Careers

As part of promoting STEM career awareness, four teachers focused on highlighting diversity. This was done through both curricula and partnerships, representing a cross-cutting theme for implementing integrated STEM. Darma noted, "every lesson has one [STEM] career and then they all have one known Hispanic or African American showing us going in there [that career]. And then I pull up, you know, people who are other race background". She explicitly showed her students that people from diverse backgrounds could be STEM professionals. Stacy embedded some of her teaching within a global context to highlight non-white scientists in Africa working on aquaponics. Allina and Clara described how their female guest speakers engaged students in discussions related to gender equity with Clara sharing, "They incorporate a lot of young women talking about the need for women in coding, women in science, women in engineering. I really tried to include the girls and let them know that there is a need for them in the future in these areas, if they learn these skills.

Clara and Darma also mentioned how their demographic of students, which included low-socioeconomic-status students, were more engaged when guest speakers talked about chances of going to college for free when pursuing STEM degrees. Interestingly, all four teachers who addressed diversity in STEM careers were women.

4. Discussion

Our findings reflect much of what has previously been found in the literature related to STEM conceptions and what STEM education entails [10,14]. This is not entirely surprising given the consensus surrounding aspects such as developing skills and including real-world connections, all while encouraging student-centered pedagogies and the integration of content from multiple disciplines [14]. Additionally, since professional development can play a role in teachers' conceptions of integrated STEM education [10,21], it is also not surprising that teachers' conceptions reflected much of what they learned in their respective workshops. Because we chose not to provide a "cookbook" approach to integrated STEM education in the workshops, teachers took the framework we presented and made it their own. Most importantly, they did this with respect to the elements explored in this study as we provided no "correct" or one way to approach content integration or the content-agnostic elements discussed in this work. Because of this, our study adds to the literature in several ways that unpack how teachers view the contribution of each discipline within integrated STEM education, how real-world problems are used to contextualize learning, how 21st century skills are included, and how STEM careers are promoted in their classrooms. The following discussion addresses how our findings may lead to a better understanding of STEM education and how to improve professional development opportunities.

4.1. The Multiplicity of Conceptions and Connections

In attending to our first research question, we found that, similar to the literature [14], teachers held multiple conceptions concerning the role of each STEM discipline within integrated STEM instruction. This did not always include clear, definitive connections among the disciplines, but included multiple avenues for the disciplines to be leveraged. For instance, in some cases, technology may relate to science as a tool to collect data, but on other occasions, as a product of an engineering design task; these two conceptions do not interfere with one another but could be complementary. This reflects the ongoing tension in the literature related to technology and its place and purpose within integrated STEM education [63,64], although it must be noted that teachers focused primarily on students' use of technology. Knowing that these connections were not always clear and teachers could potentially hold contrasting, yet complementary, conceptions of a given disciplines suggests that the nature of integration across disciplines may very well vary among classrooms and even across different activities or lessons. This is likely why having a clear vision of integrated STEM education when it comes to the number of disciplines and how disciplines are used has been challenging [14].

Our findings indicated that within science classrooms, mathematics and technology have been mostly relegated to supporting roles by providing a set of practices or tools for students, reflecting previous findings [5,18]. Despite this, our findings also suggest that teachers view these two disciplines are critical to integrated STEM education as they allow students to better understand or represent scientific ideas, help students make engineering design decisions, and assist students in developing important 21st century skills. Unlike mathematics and technology, science was viewed primarily as a knowledge base or set of facts more so than a process of learning about the world; this reflects a rather limited and positivist view of science and suggests that the content primarily being learned through integrated STEM is science. In other words, while science was something to be discovered, it was also a body of knowledge to be used by others—primarily by engineers.

Engineering was seen both as a design process to create some product and as a method to solve problems, but did not appear to include disciplinary content. The connection between these two related but separate pathways was not always clear. Engineering could be designing for the sake of design rather than designing solutions to a problem. Alternatively, engineering could provide a context for a design and a problem to solve, and additionally act as a method or process for solving that problem. In this, engineering appears to be a way to frame science teaching and provide students with something "new" and exciting to do in their class, focusing on the creation of products or projects in conjunction with learning about science concepts. This conception of engineering may reveal a rather narrow understanding, focusing primarily on the design process, that represents more of a pedagogical shift towards the inclusion of 21st century skills rather than truly incorporating another discipline into instruction.

4.2. Content-Agnostic Characteristics: An Emphasis on the Future

In attending to our second research question, it was no surprise that teachers viewed STEM education in the context of preparing students for their future, adult lives (Navy et al., 2021). Teachers' comments stressed the importance of equipping students with 21st century skills rather than preparing students with content knowledge, reflecting the shift in policy documents [1] that move away from rote memorization of scientific facts towards engaging students in STEM practices. This may suggest that science teachers have a clear separation between science teaching and integrated STEM teaching; in this, "science only" teaching may focus on content delivery and context-less laboratory investigations, versus integrated STEM teaching that focuses on a more realistic, contextualized representation of how science and STEM are used in the real-world. In this, teachers make use of real-world problems, including both local and global contexts that they believed would motivate students, similar to what has been purported in the literature [29–31]. This separation may reflect an awareness that integrated STEM is not and should not be used for all teaching as some content needs to be taught in isolation before students are ready to engage in realistic STEM practices [59].

Teachers related the need to solve problems—whether general problems or real-world problems that contextualized students learning—most readily to creativity rather than to critical thinking. Although creativity is needed in generating innovative solutions to problems, critical thinking is necessary when using data to assess how well those solutions address the problem. Generally, teacher comments about 21st century skills focused primarily on collaboration and communication, which may be "easier" or more natural to tackle in classrooms (compared to critical thinking, for example) due to their visibility and familiarity. Even though teachers emphasized the need for data analysis, teachers did not detail this process or elaborate on how they might guide students in interpreting results through critical thinking. Additionally, teachers only noted their observations of student *mis*communications in group work, suggesting that they may have overlooked groups that collaborate and communicate effectively. The authors of [65,66] have explored the criticality of small group tasks and the work here emphasizes the need to continue to explore this area through research, most notably to equip teachers with tools of their own to help develop these important skills.

The split in how STEM careers were promoted suggests that teachers either had not conceptualized integrated STEM education as a vehicle for promoting students' STEM career awareness or were lacking the knowledge or resources to do so. What is noteworthy is how four teachers, all women, focused on diversity when introducing STEM careers to their students. This suggests that teachers may need access to resources related to STEM careers [55], especially when it comes to diversity, to make direct connections in their curriculum and connections to those that might represent the local community. These kinds of resources can assist teachers in unpacking what diversity entails in STEM and how it can exclude or include certain groups of students from pursuing STEM-related careers. If teachers engage more in the promotion of STEM careers, especially in highlighting and encouraging diversity therein, then the STEM education community may start to actualize the promises made in policy documents to promote STEM for all [1,3]. This may further relate to the relevance of curriculum and the real-world problems that are selected, which should be connected to students' lives in some way for them to develop motivation and interest toward STEM [29–31].

4.3. The Bigger Vision of Integrated STEM Education

Our deeper dive into teachers' conceptions of integrated STEM education illuminates further complexities. For one, it is clear that the relationship between the STEM disciplines can vary, which is exacerbated by the fact that teachers conceptualize the content-agnostic characteristics in multiple ways. Even though the inclusion of 21st century skills has been prominently featured within the integrated STEM education literature, asserting what this means is unclear. Does implicitly including 4-Cs into instruction "count" or must there be explicit calls to the development of the 4-Cs? Answering this question may vary based on grade-level, which was not explored in the current work. While teachers shared their ideas and current approaches related to raising STEM career awareness, this characteristic was represented to a lesser extent. This work, while attempting to better understand teachers' current conceptions of integrated STEM education, reveals areas in which teachers may need additional support that includes expanding the role of mathematics beyond data analysis, informing how to explicitly address 21st century skills in their teaching, and finding resources to promote STEM career awareness.

4.4. Limitations

Our work is limited to the small sample size and underrepresentation of elementary teachers in particular; however, the exploratory nature of this work does not attempt to make claims about all K-12 teachers. For instance, all participants identified themselves as teachers of science, but our findings would likely be different if our focus was on mathematics or computer science teachers. While the work presented here did not include observations of teachers' implementation of integrated STEM education in their classrooms, teachers' responses provided a small window into their practice based on the conceptions they shared. There is still a need for a more thorough examination of how exactly science, technology, engineering, and mathematics are used in the classroom and to compare this to how teachers conceptualize the role of each discipline. With respect to 21st century skills, teachers acknowledged the need to develop some of these skills (primarily collaboration and communication), but it is unclear how much of this is currently done in their classrooms. We should also note that, when first asked to describe how "21st century skills" were used within their integrated STEM instruction, few teachers recognized the phrase and only when the interviewer clarified with examples of the 4-Cs did teachers provide more thorough responses.

5. Conclusions

This study provides valuable information related to conceptions of integrated STEM education. Additionally, this work reveals approaches in which teachers conceptualize their implementation of integrated STEM education with respect to STEM disciplines, real-world problems, 21st century skills, and promotion of STEM career awareness. Asking more pointed questions allowed us to better understand these areas so that as teacher educators, we can better support teachers. For instance, many of these teachers were new to engineering and needed support in this area; this is likely true for a large number of science teachers who are now expected to be experts in integrated STEM education. Moreover, these conceptions demonstrated a need to better understand how technology and mathematics should be included in integrated STEM education and to offer models that treat these two disciplines as more than just tools, but as a knowledge base.

Even though we asked teachers about 21st century skills and STEM careers in the context of integrated STEM education, their responses could have easily been with respect to teaching science more broadly. In this sense, these teachers better verbalized the pedagogical components of integrated STEM education than the integration of content. Focusing on pedagogy first may be a way to "ease" into shifting from science to integrated STEM teaching. Having a clear framework related to the integration of mathematics and technology beyond their supportive, tool-like and practice-based role that seems to occur in teachers' conceptions of STEM education may help to improve their integrated STEM instruction, but this is still an area in need of more attention. There is still a significant amount of work to do with respect to content integration, but studies such as the one presented here provide a clear access point to create teacher buy-in to integrated STEM education.

We make several recommendations for those working as teacher educators wishing to support science teachers as they expand their teaching to include integrated STEM. First, including teachers from multiple STEM disciplines, such as mathematics and computer science teachers, may help to further illuminate the role of mathematics and technology, as they likely have alternative understandings of integrated STEM given their teaching contexts. This may help to emphasize the different types of disciplinary integration that can happen so that mathematics and technology are not always relegated to a support role. Second, for professional development opportunities, there is a need for clearer and more explicit connections to 21st century skills and STEM careers within integrated STEM frameworks. This could come in the form of some supplemental PD to enhance one focused on the nature of STEM integration. In particular, an emphasis should be placed on the diversity of STEM professionals, not just focusing on those who are most often cited in school textbooks (e.g., Albert Einstein) that ignore historically underrepresented groups. Further, this PD could promote diversity through an empathic lens by helping teachers understand the barriers and struggles that these marginalized groups overcome before and after becoming STEM professionals. Third, teachers should also be regularly faced with articulating their STEM conception model and challenged to describe the intricacies. The disconnection between the promotion of STEM career awareness and integrated STEM curricula suggests that the integrated STEM education PD should empower teachers with the ideas and practical capability to promote students' STEM career awareness through integrated STEM lessons, especially as related to diversity within STEM careers. Further, these attempts should motivate students to pursue more STEM-related courses and seriously consider STEM careers. Finally, outside of professional development, there is a need to continue to support teachers during the implementation phases and allow them frequent opportunities to reflect on their practice. Simultaneously, as researchers, we need to closely examine how integrated STEM education plays out in classrooms and examine how these aspects are implemented.

Author Contributions: All authors conceptualized and designed the study based on previous work. K.K., B.M.H. and F.L. collected and organized all data. All authors participated in data analysis and initial draft of the manuscript. E.A.D. led revisions and final format of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was made possible by NSF grant #1854801, 1813342, and 1812794. The findings, conclusions, and opinions herein represent the views of the authors and do not necessarily represent the view of personnel affiliated with the National Science Foundation.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Due to IRB permissions, data cannot be shared outside of those directly related to the project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, USA, 2012.
2. NGSS Lead States. *Next Generation Science Standards: For States, by States*; The National Academies Press: Washington, DC, USA, 2013.
3. National Research Council. *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics*; The National Academies Press: Washington, DC, USA, 2011.
4. National Research Council. *Monitoring Progress toward Successful K-12 STEM Education: A Nation Advancing?* The National Academies Press: Washington, DC, USA, 2013.
5. Dare, E.A.; Ring-Whalen, E.A.; Roehrig, G.H. Creating a continuum of STEM models: Exploring how K-12 science teachers conceptualize STEM education. *Int. J. Sci. Educ.* **2019**, *41*, 112–144. [CrossRef]
6. Breiner, J.M.; Harkness, S.S.; Johnson, C.C.; Koehler, C.M. What is STEM? A discussion about conceptions of STEM in education and partnerships. *Sch. Sci. Math* **2012**, *112*, 3–11.
7. Bybee, R.W. Advancing STEM education: A 2020 vision. *Tech. Eng. Teach.* **2010**, *70*, 30–35.
8. Martín-Páez, T.; Aguilera, D.; Perales-Palacios, F.J.; Vílchez-González, J.M. What are we talking about when we talk about STEM education? A review of literature. *Sci. Educ.* **2019**, *103*, 799–822.
9. Navy, S.L.; Kaya, F.; Boone, B.; Brewster, C.; Calvelage, K.; Ferdous, T.; Hood, E.; Sass, L.; Zimmerman, M. "Beyond an acronym, STEM is . . . ": Perceptions of STEM. *Sch. Sci. Math* **2021**, *121*, 36–45. [CrossRef]
10. Ring-Whalen, E.A.; Dare, E.A.; Roehrig, G.H.; Titu, P.; Crotty, E.A. From conception to curricula: The role of science, technology, engineering, and mathematics in integrated STEM units. *Int. J. Educ. Math. Sci. Technol.* **2018**, *6*, 343–362. [CrossRef]
11. Bartels, S.L.; Rupe, K.M.; Lederman, J.S. Shaping preservice teachers' understandings of STEM: A collaborative math and science methods approach. *J. Sci. Teach. Educ.* **2019**, *30*, 666–680. [CrossRef]
12. Radloff, J.; Guzey, S. Investigating preservice STEM teacher conceptions of STEM education. *J. Sci. Educ. Tech.* **2016**, *25*, 759–774. [CrossRef]

13. Roehrig, G.H.; Dare, E.A.; Ellis, J.A.; Ring-Whalen, E.A. Beyond the Basics: A Detailed Conceptual Framework of Integrated STEM. *Disc. Interdisc. Sci. Ed. Rsch.* **2021**. Forthcoming.
14. Moore, T.J.; Johnston, A.C.; Glancy, A.W. STEM integration: A synthesis of conceptual frameworks and definitions. In *Handbook of Research on STEM Education*; Johnson, C.C., Mohr-Schroeder, M.J., Moore, T.J., English, L.D., Eds.; Routledge: London, UK, 2020; pp. 3–16.
15. National Academy of Engineering and National Research Council. *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research*; The National Academies Press: Washington, DC, USA, 2014.
16. Gow, L.; Kember, D. Conceptions of teaching and their relationship to student learning. *Br. J. Educ. Psychol.* **1993**, *63*, 20–33. [CrossRef]
17. Trigwell, K.; Prosser, M.; Waterhouse, F. Relations between teachers' approaches to teaching and students' approaches to learning. *High. Educ.* **1999**, *37*, 57–70. [CrossRef]
18. Ring, E.A.; Dare, E.A.; Crotty, E.A.; Roehrig, G.H. The evolution of teacher conceptions of STEM education throughout an intensive professional development experience. *J. Sci. Teach. Educ.* **2017**, *28*, 444–467. [CrossRef]
19. Luft, J.A.; Diamond, J.M.; Zhang, C.; White, D.Y. Research on K-12 STEM professional development programs: An examination of program design and teacher knowledge and practice. In *Handbook of Research on STEM Education*; Johnson, C.C., Mohr-Schroeder, M.J., Moore, T.J., English, L.D., Eds.; Routledge: London, UK, 2020; pp. 361–374.
20. Dare, E.A.; Ellis, J.A.; Roehrig, G.H. Understanding science teachers' implementations of integrated STEM curricular units through a phenomenological multiple case study. *Int. J. STEM Educ.* **2018**, *5*, 1–19. [CrossRef]
21. Du, W.; Liu, D.; Johnson, C.C.; Sondergeld, T.A.; Bolshakova, V.L.J.; Moore, T.J. The impact of integrated STEM professional development on teacher quality. *Sch. Sci. Math.* **2019**, *119*, 105–114. [CrossRef]
22. Johnson, C.C.; Sondergeld, T.A. Effective STEM professional development. In *STEM Road Map: A Framework for Integrated STEM Education*; Johnson, C.C., Peters-Burton, E.E., Moore, T.J., Eds.; NSTA Press: Arlington, VA, USA, 2015; pp. 203–210.
23. Shernoff, D.J.; Sinha, S.; Bressler, D.M.; Ginsburg, L. Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *Intnl. J. STEM Educ.* **2017**, *4*, 13. [CrossRef]
24. Wang, H.-H.; Moore, T.J.; Roehrig, G.H.; Park, M.S. STEM integration: Teacher perceptions and practice. *J. Pre-College Eng. Educ. Rsch.* **2011**, *1*, 1–13.
25. Hill, C.; Corbett, C.; St. Rose, A. *Why So Few? Women in Science, Technology, Engineering, and Mathematics*; AAUW: Washington, DC, USA, 2010.
26. Vakil, S.; Ayers, R. The racial politics of STEM education in the USA: Interrogations and explorations. *Race Ethn. Educ.* **2019**, *22*, 449–458. [CrossRef]
27. Lachapelle, C.; Cunningham, C. Engineering in elementary schools. In *Engineering in Pre-College Settings: Synthesizing Research, Policy, and Practices*; Purzer, S., Strobel, J., Cardella, M., Eds.; Purdue University Press: West Lafayette, IN, USA, 2014; pp. 61–88.
28. Monson, D.; Besser, D. Smashing milk cartons: Third-grade students solve a real-world problem using the engineering design process, collaborative group work, and integrated STEM education. *Sci. Child.* **2015**, *52*, 38–43. [CrossRef]
29. Djonko-Moore, C.; Leonard, J.; Holifield, Q.; Bailey, E.; Almughyirah, S. Using culturally relevant experiential education to enhance urban children's knowledge and engagement in science. *J. Experiential. Educ.* **2018**, *41*, 137–153. [CrossRef]
30. Moll, L.C.; Amanti, C.; Neff, D.; Gonzalez, N. Funds of knowledge for teaching: Using a qualitative approach to connect homes and classrooms. *Theory Into Pract.* **1992**, *31*, 132–141. [CrossRef]
31. Upadhyay, B.R. Using students' lived experiences in an urban science classroom: An elementary school teacher's thinking. *Sci. Educ.* **2005**, *90*, 94–110. [CrossRef]
32. Science and Engineering Indicators 2020: The State of U.S. Science and Engineering (NSB-2020-1). Available online: https://ncses.nsf.gov/pubs/nsb20201/ (accessed on 1 June 2021).
33. Partnership's Web Site. *A State leader's Action Guide to 21st Century Skills: A New Vision for Education*; Partnership for 21st Century Skills: Tucson, AZ, USA, 2006. Available online: http://apcrsi.pt/website/wp-content/uploads/20170317_Partnership_for_21st_Century_Learning.pdf (accessed on 10 November 2021).
34. Bellanca, J.; Brandt, R. *21st Century Skills: Rethinking How Students Learn*; Solution Tree Press: Bloomington, IN, USA, 2010.
35. Stehle, S.M.; Peters-Burton, E.E. Developing student 21st Century skills in selected exemplary inclusive STEM high schools. *Int. J. STEM Educ.* **2019**, *6*, 39. [CrossRef]
36. Trilling, B.; Fadel, C. *21st Century Skills: Learning for Life in Our Times*; Jossey-Bass: Hoboken, NJ, USA, 2009.
37. Bybee, R.W. *A Case for STEM Education*; NSTA Press: Arlington, VA, USA, 2013.
38. Johnson, C.E.; Peters-Burton, E.E.; Moore, T.J. *STEM Road Map: A Framework for Integrated STEM Education*; Routledge: London, UK, 2016.
39. National Education Association. *Preparing 21st Century Students for a Global Society: An Educator's Guide to the "Four Cs"*; National Education Association: Washington, DC, USA, 2012.
40. Cox, C.B. 21st Century Skills and Principles of Flow in the Foreign Language Classroom (Publication No, 4197). Master's Thesis, Brigham Young University, Provo, UT, USA, 2014.
41. Hughes, C. Theory of Knowledge aims, objectives and assessment criteria: An analysis of critical thinking descriptors. *J. Rsch. Intnl. Educ.* **2014**, *13*, 30–45. [CrossRef]
42. Browne, M.; Keeley, S. *Asking the Right Questions: A Guide to Critical Thinking*, 6th ed.; Prentice Hall: Hoboken, NJ, USA, 2001.

43. Mednick, S. The associative basis of the creative process. *Psyc. Rev.* **1962**, *69*, 220–232. [CrossRef]
44. Finke, R.A.; Ward, T.B.; Smith, S.M. *Creative Cognition: Theory, Research and Applications*; MIT Press: Cambridge, MA, USA, 1992.
45. Carpenter, J.P.; Pease, J.S. Preparing students to take responsibility for learning: The role of non-curricular learning strategies. *J. Curric. Instr.* **2013**, *7*, 38–55. [CrossRef]
46. Jonassen, D.; Strobel, J.; Lee, C.B. Everyday problem solving in engineering: Lessons for engineering educators. *J. Eng. Educ.* **2006**, *95*, 139–151. [CrossRef]
47. North Central Regional Educational Laboratory & Group. *EnGauge 21st Century Skills: Literacy in Digital Age*; North Central Regional Educational Laboratory: Naperville, IL, USA, 2003.
48. Husin, W.; Fadzilah, W.N.; Arsad, M.; Nurazidawati, O.; Oziah, H.; Lilia, R.; Sattar, M.; Osman, K.; Iksan, Z. Fostering students' 21st century skills through project oriented problem based learning (POPBL) in integrated STEM education program. *Asia-Pac. Forum Sci. Learn. Teach.* **2016**, *17*, 1–18.
49. President's Council of Advisors on Science and Technology (PCAST). Prepare and Inspire: K-12 Education in Science, Technology, Engineering and Math (STEM) for America's Future. 2010. Available online: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcaststemed-report.pdf (accessed on 1 May 2021).
50. Barth, J.M.; Masters, S. Changes in math and science interest over school transitions: Relations to classroom quality, gender stereotypes, and efficacy. *Intnl. J. Gend. Sci. Tech.* **2020**, *12*, 4–31.
51. Xie, Y.; Fang, M.; Shauman, K. STEM education. *Annu. Rev. Sociol.* **2015**, *41*, 331–357. [CrossRef]
52. Johnson, A.; Elliott, S. Culturally relevant pedagogy: A model to guide cultural transformation in STEM departments. *J. Microbiol. Biol. Educ.* **2020**, *21*, 5. [CrossRef]
53. Hazari, Z.; Sadler, P.M.; Sonnert, G. The science identity of college students: Exploring the intersection of gender, race, and ethnicity. *J. Coll. Sci. Teach.* **2013**, *42*, 82–91.
54. Upadhyay, B.; Atwood, E.; Tharu, B. Actions for sociopolitical consciousness in a high school science class: A case study of ninth grade class with predominantly indigenous students. *J. Rsch. Sci. Teach.* **2020**, *57*, 1119–1147. [CrossRef]
55. Cohen, C.; Patterson, D.G.; Kovarik, D.N.; Chowning, J.T. Fostering STEM career awareness: Emerging opportunities for teachers. *Wash. State Kappan* **2013**, *6*, 12–17.
56. Knowles, J.G.; Kelley, T.R.; Holland, J.D. Increasing teacher awareness of STEM careers. *J. STEM Educ.* **2018**, *19*, 47–55.
57. Merriam, S.B. *Qualitative Research and Case Study Applications in Education: Revised and Expanded from Case Study Research in Education*; Jossey-Bass Publishers: Hoboken, NJ, USA, 1998.
58. Mills, A.J.; Durepos, G.; Wiebe, E. (Eds.) *Encyclopedia of Case Study Research*; SAGE: Thousand Oaks, CA, USA, 2009.
59. Kelley, T.R.; Knowles, J.G. A conceptual framework for integrated STEM education. *Intnl. J. STEM Educ.* **2016**, *3*, 2–11. [CrossRef]
60. Dare, E.A.; Ring-Whalen, E.A. Eliciting and refining conceptions of STEM education: A series of activities of professional development. *Innov. Sci. Teach. Educ.* **2021**, *6*, 1–19.
61. Corbin, J.; Strauss, A. *Basics of Qualitative Research*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2015.
62. Miles, M.B.; Huberman, A.M.; Saldaña, J. *Qualitative Data Analysis: A Methods Sourcebook*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2019.
63. Ellis, J.A.; Wieselmann, J.R.; Sivaraj, R.; Roehrig, G.H.; Dare, E.A.; Ring-Whalen, E.A. Toward a productive definition of technology in science and STEM education. *Contemp. Issues in Tech. and Teach. Educ.* **2020**, *20*, 472–496.
64. Cullen, T.; Guo, M. The nature of technology. In *Critical Questions in STEM Education*; Akerson, V.L., Buck, G.A., Eds.; Springer: New York, NY, USA, 2020; pp. 21–32.
65. Wieselmann, J.R.; Dare, E.A.; Ring-Whalen, E.A.; Roehrig, G.H. "I just do what the boys tell me": Exploring small group student interactions in an integrated STEM unit. *J. Rsch. Sci. Teach.* **2020**, *57*, 112–144. [CrossRef]
66. Wieselmann, J.R.; Dare, E.A.; Ring-Whalen, E.A.; Roehrig, G.H. "There are other ways to help besides using the stuff": Using activity theory to understand dynamic student participation in small group activities. *J. Rsch. Sci. Teach.* **2021**, *58*, 1281–1319. [CrossRef]

education sciences

MDPI

Article

Undergraduate Engineering and Education Students Reflect on Their Interdisciplinary Teamwork Experiences Following Transition to Virtual Instruction Caused by COVID-19

Kristie S. Gutierrez [1,*], Jennifer J. Kidd [1], Min Jung Lee [1], Pilar Pazos [2], Krishnanand Kaipa [3], Stacie I. Ringleb [3] and Orlando Ayala [4]

[1] Department of Teaching & Learning, Old Dominion University, Norfolk, VA 23529, USA
[2] Department of Engineering Management and Systems Engineering, Old Dominion University, Norfolk, VA 23529, USA
[3] Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, VA 23529, USA
[4] Department of Engineering Technology, Old Dominion University, Norfolk, VA 23529, USA
* Correspondence: kgutierr@odu.edu

Abstract: This study explores undergraduate engineering and education students' perspectives on their interdisciplinary teams throughout the rapid transition to online learning and instruction from a face-to-face to a virtual format. In this qualitative study, students' reflections and focus groups from three interdisciplinary collaborations were analyzed using the lens of Social Cognitive Theory. COVID-19 created a dramatic change in the environment such that the most immediate and direct impact on students' experiences was on the environmental aspects of Bandura's triadic reciprocal determinism model, which then triggered behavioral and personal responses to adapt to the new environment. Subsequent evidence of reciprocal effects between environmental, behavioral, and personal factors took place as students continued to adapt. Results suggest that the modifications made to transition the project fully online were meaningful experiences for students' learning and teaching of engineering through teams. This interdisciplinary partnership provided both pre-service teachers and undergraduate engineering students with the opportunity to learn and practice content and professional skills that will be essential for success in future work environments.

Keywords: interdisciplinary teams; engineering education; pre-service teacher education; partnerships; social cognitive theory

Citation: Gutierrez, K.S.; Kidd, J.J.; Lee, M.J.; Pazos, P.; Kaipa, K.; Ringleb, S.I.; Ayala, O. Undergraduate Engineering and Education Students Reflect on Their Interdisciplinary Teamwork Experiences Following Transition to Virtual Instruction Caused by COVID-19. *Educ. Sci.* **2022**, *12*, 623. https://doi.org/10.3390/educsci12090623

Academic Editors: Andrea Burrows and Mike Borowczak

Received: 31 July 2022
Accepted: 10 September 2022
Published: 15 September 2022

1. Introduction

Ed+gineering is a National Science Foundation (NSF) funded program that partners undergraduate engineering students and pre-service teachers (PSTs) (i.e., students in a teacher preparation program) in small interdisciplinary teams to teach engineering lessons to elementary school students. In March 2020, as most schools and universities in the US shifted to online teaching due to COVID-19, Ed+gineering also had to adapt its hands-on engineering activities to a virtual format. The education and engineering courses in which the undergraduates were enrolled transitioned from face-to-face to online delivery, and thus the delivery mode for the lessons for the elementary students had to transition as well, moving to either synchronous or asynchronous online instruction. The transition to online learning affected many aspects of college students' experiences, including their collaboration with their peers and the learning associated with their team interactions.

While much is known about online engineering education [1], little is understood about how the Spring 2020 mid-semester emergency transition to online learning affected K-20 students' experiences learning engineering. Moreover, there is a lack of student voices in the literature, and few descriptions of how students managed the challenges of transitioning online and how they perceived the impact on their learning during this unexpected shift.

As COVID-19 continues to reshape education, it is critical for educators, in both pre- and post-secondary environments, to understand how students were impacted by the transition and how hands-on engineering experiences can be supported in virtual environments. This study examines how the COVID-19 context and shift to online instruction influenced engineering students' and PSTs' learning experiences and team dynamics as they worked in a cross-disciplinary context to adapt and deliver engineering lessons to elementary school students in a virtual format.

2. Background

This paper focuses on the interdisciplinary collaborative experiences of future engineers and teachers as they transitioned to online learning at the onset of the COVID-19 pandemic. In the following section, we ground the work in relevant literature on teaching and learning engineering in online settings, especially the challenges of supporting students' teamwork in a virtual context.

2.1. Teaching and Learning Engineering Online during the COVID-19 Pandemic

After COVID-19 forced schools to shift online unexpectedly, studies that investigated the transition's impact on teaching and learning in higher education settings, and specifically in engineering education, slowly emerged. A plethora of recent articles (e.g., [2–6]) have examined the ways in which universities have adapted to meet the instructional needs of their students. O'Dea and Stern [4] led a special issue in the *British Journal of Educational Technology* where they summarized findings from seven included studies. Notably, the studies suggest that "simply moving teaching content and activities from face-to-face to online environments will not work. They need to be redesigned to suit online learning," and that use of technology in the COVID-19 shift online is critical; however, "technology on its own will not address the educational needs and challenges staff and students face in online environments," rather pedagogical approaches should be designed and used effectively for the specific learning platforms (p. 440). Relatedly, Barr et al. [7] shared how course instructors made many modifications to adapt to online teaching, some of which worked well (e.g., weekly online multiple-choice quizzes, flipped classroom strategy, and links to additional materials) and others that did not (e.g., group activities, faster pace). Reports enumerated logistical challenges, such as lack of infrastructure (e.g., computer hardware and internet access/connectivity) for learning/teaching engineering online, while students expressed a lack of motivation, engagement, and communication with instructors in the Zoom environment [8]. Rassudov and Korunets [9] noted the major challenge of preparing future engineers to operate hardware that can simply not be made available to students at home. In a study about the impact of the COVID-induced migration to online instruction for clinical courses (i.e., nursing, medical sciences, biology, and chemistry), Jeffries et al. [3] shared that some "educators [. . .] made use of items available to [university] students at home, such as a cup of coffee to teach the principles of specific heat capacity" (p. S105).

Regarding teaching modality, most educators opted for either asynchronous sessions accompanied by interactions based on email, forums, or chat or synchronous sessions to replicate the interaction of face-to-face settings [5,6]. However, students reported low satisfaction and felt overwhelmed by those modalities for various reasons (e.g., Zoom fatigue, lack of interaction, and dynamic learning), categorically proposing the reduction of the academic workload in general [6]. Thus, "the process of adaptation to virtuality was not taking place in the best conditions, at least with regard to students" [6] (p. 217). To understand students' fatigue, educators first need to understand that as much as they were forced to look for new strategies and technologies to adapt the transition to online teaching, students have also been forced to adapt to those new modalities and instructions. As a result, they were required to do additional time management, discipline, and organization to meet those new learning modalities [5]. While there are studies that have examined how students manage their personal learning, there are few that examine their learning experiences in a team context during this unexpected shift.

Studies represented in O'Dea and Stern [4] also emphasized the specific needs of learners in virtual spaces, particularly the need for "quality communication and social interactions" as these are important "to build an inclusive online learning environment" (p. 440). Social interactions may be inhibited in online settings [10,11], and some studies reported impediments to group projects due to difficulties coordinating schedules and learning new software for online meetings [7,12]. On a positive note, García Aretio [2] argued that it is possible to form "affective and emotional ties" with their peers and instructors in online settings (p. 15). As a result, researchers emphasize interaction, especially between the student and the teacher, as one of the central elements of online education [5,13]. Vielma and Brey [12] saw this time as an opportunity to train students in the best practices for remote collaboration as engineering work is becoming increasingly global, requiring virtual communication. Relatedly, Ed+gineering's research during this period found that interdisciplinary teams of education and engineering students were able to develop and hone communication and collaboration skills during a virtual engineering lesson project [14]. Continuous team communication and collaboration in a time of imposed isolation became an important source of emotional connection [2] as well as an opportunity for interpersonal skill development in a virtual setting.

2.2. Teamwork in Engineering & Engineering Education

Although engaging in collaborative work as part of courses has been linked to enhanced learning outcomes [15,16], the most significant benefit of teaching teamwork skills in an academic setting is their transferability to the workplace [17]. The growing complexity of the global economy demands increased cooperation and coordination between people with diverse expertise [18]. Thus, a workforce equipped with teamwork skills is critical to face the rapidly changing and global nature of the business context [19]. In particular, teamwork and communication skills are recognized as essential competencies in engineering practice [20–22] and in other disciplines [18,19,23], including teaching [24]. Furthermore, recent research indicates that effective teamwork results in higher quality outcomes and products [25].

Considering the need to prepare future engineers who can collaborate effectively across geographic space and academic disciplines, more research is needed to understand how to best do this. When students learn and collaborate in online contexts, they process the social information available to them [26]. They use this information to develop social structures and patterns of interaction (e.g., signaling a desire to speak) to accomplish their individual and collective goals [11]. While the development of social structures typically takes place seamlessly in face-to-face environments, establishing social connections is more challenging in online learning environments because communication channels are less rich and thereby less suitable for transmitting non-verbal cues [10,11]. Not surprisingly, virtual contexts have been found to be less conducive to establishing trust than face-to-face contexts [27–29]. Accordingly, students collaborating online may face more challenges and/or require additional support structures.

This study explores the team interactions of engineering and education students as they collaborated online to design and teach engineering lessons to elementary school students. While a handful of studies explored the challenges of teaching and learning engineering during the pandemic, there is a lack of student voice in this literature and little focus on how students engaged in teamwork navigated the challenge of transitioning online and how this experience influenced their learning.

3. Theoretical Framework

Social Cognitive Theory (SCT) [30] can be applied to the pandemic timeline to help explain how environmental, personal, and behavioral factors affected students' educational experiences as they navigated the new COVID-19 learning landscape. The SCT framework explores three major factors—environmental, personal, and behavioral—to frame an individual's learning in a social context. In particular, it considers how individuals decide which behaviors to enact in light of their social environment. In addition to environmental factors, students' personal factors, including their past experiences, thoughts, beliefs, and feelings, also affect how they behave [30]. Bandura explains that the influence of the factors is reciprocal, accordingly, students' actions may, in turn, influence their thoughts and emotions. He goes as far as to say that an individual's brain and mental structures can be modified through their behavior [31]. Furthermore, people learn vicariously, by watching others [31], so a person's personal cognitive processes can also be modified by their environment.

Schunk and DiBenedetto [32] explored the SCT framework and identified key components of the three factors. They describe a person's choice of activities, persistence, and achievement as behavioral factors that contribute to one's motivation. Personal factors, on the other hand, reflect individual learner characteristics associated with a person's beliefs and cognition, which are largely intangible. They include an individual's cognition, beliefs, perceptions, emotions, goals, self-efficacy, values, outcome expectations, and attributions [32]. The final group, environmental factors, refers to the context in which behaviors occur, including not only people's physical environment but also their social environment. In other words, the attitudes and beliefs of people inhabiting the same space as an individual can be considered environmental factors.

SCT suggests that personal, behavioral, and environmental factors of the learner interact and influence each other through a bidirectional causation model called triadic reciprocal determinism [31]. Bandura posits that, depending on the context, the direction and strength of the interaction between these factors vary. For example, in face-to-face learning, the physical environment of the classroom, including the behavior of students and teachers, are environmental factors that may have a powerful effect on how a student behaves and feels. In contrast, in an asynchronous online learning environment, the behavior of students and teachers may have far less impact on a student's learning experience. For example, a shy student might be willing to express frustration to his teammates through an online discussion board, whereas he might remain silent in a face-to-face team meeting.

In order to better understand how SCT can help explain the adaptation process in the transition to online learning, consider a scenario where an engineering student is struggling with her robot prototype. Imagine the scenario first in a face-to-face context inside a traditional classroom, and next in an online learning environment. We classify factors that affect the student as she interacts in this space by listing the words *environmental*, *personal*, or *behavioral* in parenthesis after the factor is first mentioned:

In a face-to-face class, a female engineering student is struggling to understand why her robot is not performing as expected. The course instructor, noticing a look of confusion, may walk up to the student, encouraging the student to ask a question (environmental factor) that leads the student to identify the problem (behavioral factor), or the student may look around (behavioral factor) and see her peers working diligently on their own prototypes. There may be a peer beside her in the classroom (environmental factor) with which she compares her design (behavioral factor). Seeing the other student's design may cause her to adjust her own prototype (behavioral factor). If her adjustment is successful, it may lead to an affective response, such as feeling more self-efficacious (personal factor), which helps her persevere in the activity (behavioral factor). If this same student shifts to an online learning environment, she is likely to have a different experience due to the different environment in which she is learning and perhaps her lack of familiarity with that environment (personal factor). She may not be able to see peers working around her (environmental factor); her teacher may not be able to observe her confused expression (environmental factor); and she may not be willing (or have the know-how) to ask a question in the online setting (personal factor). Without feedback from her peers and instructor (environmental factor), the student may not persevere (behavioral factor) and achieve a successful design. As a consequence, she may lose confidence in her ability and/or experience a decrease in motivation (personal factor). In order to successfully navigate her new online environment, the student may need to change her behaviors. If she does not, she may risk failure.

Through this example, it becomes apparent how environmental, behavioral, and personal factors interact and influence each other. Figure 1 illustrates this study's theoretical framework based on Bandura's triadic model of reciprocal determinism.

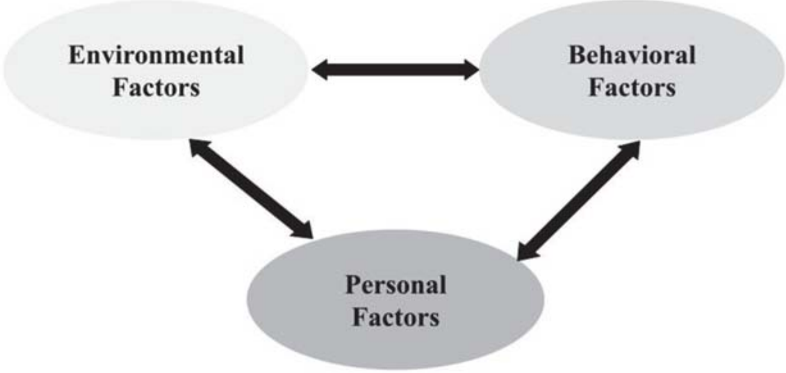


Figure 1. Bandura's Triadic Model of Reciprocal Determinism.

4. Research Question

This study examines how the COVID-19 context and shift to online learning influenced the experiences of engineering students and PSTs as they collaborated to adapt engineering lessons to a virtual format and deliver these lessons to elementary school students. It describes students' experiences through the lens of Bandura's theory of reciprocal determinism to consider how environmental, personal, and behavioral factors interacted to create students' realities post-transition. The research explores how the virtual learning context imposed by COVID-19 influenced students' abilities to function effectively as a team. This includes an examination of how interacting remotely via digital technologies influenced their collaboration, as well as a look into how, and how well, teams adapted from their face-to-face lessons into virtual ones. The specific research question is: *How did the COVID-19 adaptation to a virtual context affect undergraduate students' teamwork experiences?*

5. Materials & Methods

5.1. Research Context

Ed+gineering partnered undergraduate engineering students and pre-service teachers (PSTs) in a minority serving institution in the southeastern US to learn from, and with, each other as they planned and delivered engineering lessons to 4th and 5th graders. The project involved three course-based collaborative projects between two college student disciplines (Figure 2), heretofore referred to as Collaborations. Collaboration 1 (C1) partnered students taking a 100-level engineering class that focused on information literacy with PSTs in their first education course. Collaboration 2 (C2) occurred between engineering students studying electro-mechanical systems and PSTs in an educational technology course. Finally, Collaboration 3 (C3) involved engineering students studying fluid dynamics and PSTs enrolled in an elementary science methods course. To facilitate communication and teamwork, each team of 2–6 college students met outside of class at the start of the project to create a team charter in which they agreed upon team norms. Additionally, each team used a collaborative team Google Site/Drive for sharing team documents. The teams only worked together during the individual collaborations; at the end of each semester, the teams were dissolved. If a student takes a second Ed+gineering course in a subsequent semester, they will be partnered with new team members.

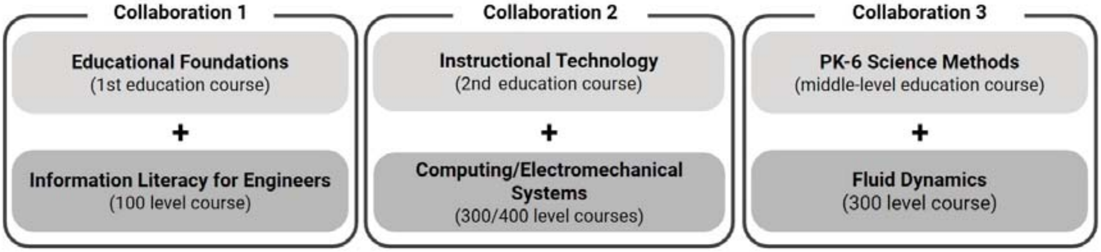


Figure 2. Ed+gineering Participating Courses by Collaboration.

Prior to school closures, all six semester-long courses were being held face-to-face, and the three collaborations were underway based on the original project design. In the following section, we will explain how the study context changed for each collaboration after transitioning online.

5.1.1. Collaboration 1

At the time of the transition to online learning due to COVID-19, the students in Collaboration 1 had already begun working in their small groups of 2–3 engineering students and 2–3 PSTs across 19 teams. They had met several times, both inside and outside of class, to collaboratively prepare for a 1 h face-to-face lesson with about a dozen 5th grade students. The lessons were centered around an engineering challenge, designing either an airdrop package or a windmill. When the pandemic forced the university to move instruction online, teams were likewise forced to move their interactions online and to change the delivery mode for their engineering lessons for the fifth graders from face-to-face to online and asynchronous. To promote interactivity in the asynchronous lessons created in Google Slides, the course instructors encouraged teams to use educational technologies, such as voice recordings, Padlet, Google Forms, etc.

All nineteen teams produced a virtual engineering lesson targeted at a 5th grade audience, and these were distributed to twelve teachers in local public and private schools. While the hope was that the lessons would be shared synchronously during in-service teachers' class sessions, to our knowledge, only one teacher used a lesson this way. One teacher assigned the lesson as an extra credit assignment, while the remaining teachers either posted it as an extra, no-credit assignment, or did not share it with students at all. There is no way to know for certain how many children completed the lesson, but eighteen elementary students submitted a picture and description of their solutions to a contest solicitation embedded within the lesson slideshows.

5.1.2. Collaboration 2

Prior to the university's pandemic-induced transition to online learning, Collaboration 2 (C2) was planned to take place in an after-school technology club for 5th graders. The technology club was led by the second author and her education students enrolled in the collaborating instructional technology course. As part of their class activities, the PSTs were responsible for helping lead each weekly club meeting throughout the entire semester, which met during their course time. The engineering project was planned to span the last five weeks of the club, with the engineering students joining three of the club sessions to help guide the development of bio-inspired robots. The plan was for each team, composed of one PST, one engineering student, and one 5th-grade student, to collaboratively build a bio-inspired robot to address a global challenge. Prior to the transition online, the PST and engineering students had met inside and outside of class to prepare to teach their elementary student partners how to code and build a robot. The PSTs and the 5th graders began their club meetings in person at the school site as planned a few weeks prior to the transition online. This allowed the PSTs and 5th graders time to establish relationships face-to-face. After the transition, the engineering project had to move online, which meant each team of one PST, one engineering student, and one 5th-grade student had to meet online synchronously via Zoom rather than in person at the school. The teams met during the regular club time and persevered in their goal to design, build, and code bio-inspired robots. Each team selected a global challenge and brainstormed ideas for how a bio-inspired robot could help address that challenge. For example, one team developed dolphin-inspired robots with snouts that could scoop up trash from the ocean floor. Most teams met for four or five, 2 h Zoom sessions in order to complete the project. In previous semesters, each team shared one robotics kit and built a single robot. Given that team members were geographically separated as a result of the COVID transition, each team member—PST, engineering student, and 5th grader—received their own individual robotics kit to use, and all were encouraged to build their own robots.

5.1.3. Collaboration 3

There were a total of seven teams in Collaboration 3 (C3). Each team was composed of two to three engineering students and two PSTs. Prior to transitioning online, each team had three in-person meetings to prepare to teach a two-hour face-to-face engineering lesson for a class of approximately 20 4th graders. Unlike in C1, teams in C3 had been able to visit their local partnered 4th-grade classrooms early in the Spring 2020 semester to introduce themselves and the engineering discipline and engineering design process, and to explore the personal interests of the students they would be teaching. Each team presented twelve different fluid mechanics topics (e.g., water parks, cooking, submarines, and slime) and asked their 4th grade students to vote for the top three topics that they would most like to learn more about.

As with C1, teams in C3 were asked to switch gears and prepare an interactive multimedia Google Slideshow following the transition online. However, their lessons were specifically designed to address the interests of the 4th grade classroom they visited. Each team's virtual lesson was sent to their partnered 4th grade classroom teacher, as well as to the other six in-service teachers participating in the collaboration. Unfortunately, only a few elementary students interacted with the lessons, even though the 4th graders were encouraged to enter a contest for participation prizes. The lack of lesson engagement in C1 and C3 was largely due to two factors: (1) teachers were mandated to only use district-produced instructional packets for their students because the district did not want to provide inequitable experiences for students who may not have had technology access, and (2) teachers were already overburdened and stressed due to the rapid shift online.

5.2. Student Participants

Table 1 describes the demographic characteristics of the PSTs and engineering student participants. Approximately 42% of the college students identified as people of color. The majority of engineering students identified as male (81%), and the majority of education students identified as female (76%). The polarized gender disparity between the engineering and education majors and the percentage of people of color in this study mirrors the student populations within the disciplines that are represented and the university as a whole, respectively.

Table 1. Student Demographics (%) for Collaborations 1–3 in the COVID-19 Transition Semester.

		Race/Ethnicity (%)					**Gender (%)**			**Class Standing (%)**			
		B	L	W	O	*n*/p	M	F	*n*/p	FY	So	Jr	Sr
C1	UES *n* = 39	21	3	56	8	13	74	13	13	56	33	3	8
	PST *n* = 58	22	3	43	5	26	21	52	27	1	25	51	23
C2	UES *n* = 18	6	11	67	6	6	78	17	5	-	6	44	50
	PST *n* = 21	24	5	67	-	5	5	91	4	-	15	55	30
C3	UES *n* = 28	21	4	61	11	4	93	4	3	-	-	7	93
	PST *n* = 13	31	15	54	-	-	15	85	-	-	-	38	62

Note. UES = Undergraduate engineering student; B = Black; L = Latin (x); W = White; O = Other; n/p = not provided; M = Male; F = Female; FY = First-Year; So = Sophomore; Jr = Junior; Sr = Senior.

5.3. Data Collection & Analysis

Ed+gineering's research, based in the southeastern US, examined changes in engineering students' and PSTs' engineering attitudes, knowledge, and teamwork skills using quantitative and qualitative assessments. To understand students' collaborative team experiences and personal learning as they transitioned to virtual settings, the researchers collected written short-answer reflections and led focus group interviews at the end of the semester.

Reflections included about 30 questions targeting various aspects of the project, such as teamwork (e.g., What roles did you and others in the team play in planning and delivering the lesson? How did the work balance change after moving online?), planning and practicing an engineering lesson (e.g., How did you plan to have the elementary students engage in the engineering design process during your lesson?), and attitudes toward engineering education (e.g., How valuable was this Engineering Lessons Project?). Additional questions (e.g., How did moving to a virtual lesson change the way this project affected you?) were specifically added to thoroughly examine the impact of the COVID-19 transition on students' experiences.

To collect engineering student and PST experiences in a more collaborative setting, we also conducted virtual focus groups via Zoom for both populations and for each collaboration. Focus groups were led by project team members who were not directly involved in the students' collaboration. Each focus group lasted between 30 and 60 min, depending on the number of students in the group. During the focus groups, questions regarding students' overall experiences with the project and specific virtual-related experiences were posed, including "What were the challenges of participating in the Ed+gineering project?" and "How did moving to a virtual environment affect your collaboration with your teammates?" Table 2 provides additional information on the reflections and focus groups for each collaboration.

Table 2. Summary of Students in Each Collaboration and Data Sources.

	Collaboration 1	**Collaboration 2**	**Collaboration 3**
Reflections (~30 questions)	18 UESs 33 PSTs	15 UESs 19 PSTs	23 UESs 11 PSTs
Focus Group (~20 questions; 30–60 min)	1 group of UESs (*n* = 5) 2 groups of PSTs (*n* = 4, each)	2 groups of UESs (*n* = 9, each) 4 groups of PSTs (*n* = 5, each)	1 group of UESs (*n* = 5) 1 group of PSTs (*n* = 5)

Note. UES = Undergraduate engineering student.

As the collected data was part of a larger investigation, only responses directly linked to the COVID-19-induced transition were coded for this study. This included responses to COVID-related questions—such as, "How did moving to a virtual lesson change the way this project affected you?", and "Did you learn different knowledge or skills preparing for an online lesson than you learned preparing for a face-to-face lesson?", as well as COVID-related responses to non-transition specific questions (e.g., "What did you learn about engineering? about teaching? about working with other people?"), such as responses that referred to virtual learning or teaching. For example, when stating what they had learned from the project, PSTs often named online teaching practices, such as not filling a slide with too much text.

The research team followed steps to develop a theoretically valid protocol for qualitative content analysis [33]. Following the identification of the purpose of data analysis (i.e., exploring the impact of the COVID-19 transition to online learning on education and engineering students' team dynamics and related learning as they collaboratively developed an elementary-level engineering lesson for online delivery), the three lead researchers built a coherent set of codes by reviewing the data for each collaboration and categorizing students' responses into the three factors of SCT: behavioral, environmental, and personal. Within each factor, they determined emergent patterns, then negotiated common codes to be used across all three collaborations.

Students' actions, conditions/situations, and reflections on their internal conditions were coded as behavioral, environmental, and personal factors, respectively. This study considers the student as the unit of analysis, and therefore, anything outside of the boundaries of the student is considered part of the environment. As a result, a codebook based on SCT constructs was built. The researchers held preliminary tryouts to test the codes on a subset of the data to ensure that all relevant data could be coded within the generated codebook. To establish inter-coder reliability, the researchers coded a subset (10%) of students' reflections and focus groups, negotiating codes and providing exemplar quotes within the established codebook, until the researchers came to a 100% agreement. Using the agreed upon codes and the established codebook, the three researchers independently coded all remaining reflections and focus groups, one researcher for each collaboration.

6. Results

Social Cognitive Theory (SCT) [30] was used to holistically examine the education and engineering students' experiences during the transition to virtual learning as a result of the COVID-19 pandemic. Informed by Bandura's triadic model of reciprocal determinism [30], the researchers considered how environmental, personal, and behavioral factors shaped students' teamwork-related interactions and learning. The individual students were the units of analysis to which the SCT framework was applied; it is their collective voice that the findings and discussion convey. This section attempts to examine how the COVID-induced changes in students' environments influenced their experiences and to uncover common and important relationships within and between the SCT factors. Thus, this study explores the influence the move to online learning had on the college students' teamwork experiences.

The mid-semester transition to online learning led to a rapid shift in team expectations and interactions. First, the goal that the teams were attempting to meet changed. Instead of preparing to deliver face-to-face engineering lessons for elementary students, the teams had to shift gears to prepare for a virtual delivery. Second, the teams no longer had the opportunity to meet face-to-face; all communication had to occur virtually. In addition, informal interactions that may have occurred before, during, and after class sessions were eliminated. Accordingly, students had to find new ways to interact to meet their goal. In sum, the COVID-19 adaptation put significant new demands on teams. Team members had to first come to a common understanding of their new goal and then formulate a plan for achieving the goal within their new virtual context. Thus, the change in the engineering lesson delivery mode and the changes in the university "classroom" environment influenced students' team environments, team behaviors, and their personal learning and affective responses related to these teamwork experiences. The following sections describe how teams' interactions were affected by the changes in environmental factors and what they learned from their online interactions. The interplay among the environmental, behavioral, and personal factors of Bandura's model of reciprocal determinism is also examined here with regard to the changes in team expectations and team environments as a result of the project's transition online.

6.1. Impact of the Online Transition on Team Interactions

Students differed in their perceptions of the impact of the online shift on team interactions. Some students perceived little difference in how they interacted with their teammates, explaining that neither their team environment nor their team behaviors changed much. Others reported positive and/or negative impacts. These students tended to name specific ways in which their team behaviors changed as a result of the online transition.

Students who perceived minimal impact on their teamwork were primarily participating in Collaborations 1 or 3. These students indicated that their teammate interactions changed only slightly because they initially met with their teammates online and continued to do so throughout the semester. They also perceived their team members' work effort and team roles to remain consistent throughout the project. Early in the semester, teams created a charter outlining team norms (e.g., team roles and responsibilities) for how they would successfully collaborate during the semester [15]. Some teams were able to adhere to the norms laid out in their charters, maintaining the original roles and meeting times despite the university's move to online instruction and the alteration in the team assignment. With social structures already in place, these students did not perceive a drastic change in their team functioning post-transition. A PST in C3 described her team's context following the transition online, sharing that, "there were minimal changes to the dynamic of our group. The group and I still stayed consistent with our meetings every Wednesday at 6 p.m. The roles and also productivity maintained the same".

On the other hand, more than two-thirds of responses did report changes in team communication or meetings. Changes related to the frequency of meetings, the roles and responsibilities of the team members, and the technologies used to support team interactions. Many teams reported increased communication amongst team members. This increase was at times attributed to the change in meeting modality and other times to an increase in the workload related to the revised assignment (i.e., planning a virtual rather than face-to-face lesson). Many teams reported needing to increase their formal communication since they were not able to informally check-in before/during/after class as they had done previously. This was especially evident in C3, where the classes had been meeting concurrently in neighboring classrooms. A few teams found they had additional time to collaborate with peers given the elimination of their school commute and the cancellation of other extracurricular activities. Others noted that the virtual format placed greater demands on their time. Some teams explained that prior to the transition, they were able to get work done collaboratively during their face-to-face meetings; however, they did not feel as productive in their online meetings and were left with a significant workload to accomplish outside of scheduled meetings. Most reflections indicated that teams expended additional time and/or effort to prepare for their online lessons and that students perceived this as an increase in their team's workload. Many students found the new expectation to convert their face-to-face engineering lesson to a virtual format confusing and bringing their team to a shared understanding of the new goal took time, especially online. For example, a PST in C1 explained that the challenge of making a virtual lesson was compounded "since we could not meet in person with our team".

Students indicated that they had to re-think the logistics of their lessons as well as the logistics of planning for their lessons. Both C1 and C3 students described changes in the structure of team tasks; rather than working collaboratively to create slide content in real-time, the team would assign specific slides to team members to complete independently.

Students seemed to feel more pressure when designated individual responsibilities. Many students stressed the importance of studying the content they were assigned to teach the elementary students and practicing engineering tasks they were assigned to demonstrate in their lessons. An engineering student from C3 also shared that:

> *"As a result of me having to teach the education students and the elementary students, I found myself looking back at the lessons to ensure my understanding of the topic before teaching it. Thus, I studied more diligently so I could teach the topics."*

For C1 and C3 students who were recording audio and video files to embed in their slideshows, it was important to have accurate information that was well presented. Students reported recording and re-recording their multimedia slides multiple times and feeling anxious about their performance. C2 students, particularly PSTs, were motivated to spend additional time preparing for their synchronous Zoom lessons, so they would feel confident teaching their 5th grade partners, knowing they would not have others (e.g., other classmates, teaching assistants, or the instructors) to rely upon during the live sessions. A PST in C2 was thankful for the additional time she had to prepare for her lesson:

> *"I think that was something that was unique about moving online. It just gave us a lot more time to prepare [...] because I was able to code and play with things before the meeting when I had time that I wouldn't have had access to if it were just the normal in-class meetings."*

Many teams reported improvement in their communication post-transition, often because they developed successful new protocols, such as meeting via Zoom prior to teaching lessons (C2). A PST in C2 explained that it actually helped her team better prepare—"I would set up 2 h Zoom meetings for us [her and her engineering partner] prior to each of our lessons [for the elementary students], so that we could make sure we were on the same page and figure out any problems". Some students shared that they became closer to their teammates as a result of facing similar pandemic hardships. When students lost the opportunity to interact face-to-face with their peers and instructors after the campus closed, team meetings became one of the very few opportunities for synchronous exchanges with classmates. Thus, despite the obvious disruption caused by the online transition and the added stress on team members when team tasks were shifted from collective to individual responsibilities, many students reported a positive shift in their team context due to more focused and frequent online team meetings, organized task assignments, and/or new bonding with their teammates.

Not all students perceived positive changes in their team's environment. Some students reported primarily negative impacts from the transition online. Engineering students often reported logistical difficulties with time and scheduling following the transition. For example, one engineering student in C2 was unable to attend the planning meeting where the elementary student and PST decided how they wanted to build their robots. Another engineering student in C3 explained that "it was challenging to find times to meet with my group after the effects of the coronavirus caused us to not be able to go to school to meet." Some engineering students complained that there was not enough time for them to help their PST and elementary students build their robots due to another engineering class that began shortly before the online club session was over. While many students attributed collaboration difficulties to scheduling or the challenge of getting used to communicating with their teams virtually, others did not pinpoint a specific cause but reported a reduction in productivity, communication, and work quality in their team. A few students characterized this as a loss of "connection" as a group. Others experienced a rollercoaster of ups-and-downs with their teams throughout the semester as environmental factors related to COVID-19 and assignment changes were introduced and modifications to team tasks were made.

Some students stopped participating post-transition, and a few withdrew from their courses. Many impacted teammates expressed stress and frustration as they tried to compensate for unresponsive teammates. There were teams where an unresponsive teammate derailed an entire group, but interestingly, there were also positive outcomes. Some students, while initially frustrated, ultimately gained confidence when they successfully assumed responsibilities neglected by their teammates. This experience was conveyed by a PST in C2:

> *"After realizing I was not going to have the engineering partner with me in-person to help with the coding, I was definitely not confident that I would be able to accomplish much with this project. But once I started working on my own, I realized it wasn't so bad and gained confidence after learning to do it on my own."*

Students' choice of technology to facilitate their online interactions also influenced their teamwork. Their choice of tools was often related to their collaboration and lesson delivery mode. C1 and C3 teams were preparing asynchronous lessons, so they may have defaulted to using asynchronous communication tools, such as email and texts, whereas C2 teams were preparing for synchronous Zoom lessons and may have found it convenient to use the same medium for lesson preparation (e.g., several teams reported joining their Zoom link an hour or two in advance of their teaching sessions in order to plan). These choices worked well for C2 teams and for some C1 and C3 teams; however, many C1 teams reported difficulty eliciting responses from teammates through asynchronous communication modes. Research by van Tryona and Bishop [11] found that establishing social connections is challenging in online learning environments where non-verbal communication cues are minimized (e.g., texting platforms, discussion boards). Teams that met synchronously seemed to maintain better social connections than teams that elected to use asynchronous tools. For example, a PST in C2 remarked, "I actually think moving to this [virtual] setting increased my interactions, and the quality of the interactions, with Jack [pseudonym]. We would meet for a full hour before Mikey [pseudonym] (5th grader) got on [line] to plan." Being able to see and hear their teammates may have generated a sense of obligation in these students, which motivated them to be responsive to their teammates' needs. The online Google Sites/Drives used by each team to facilitate communication and file sharing [15] continued to provide support for team interactions throughout the semester. Many teams indicated that it became more beneficial following the transition, especially as a shared repository for their team files.

Applying Bandura's triadic model of reciprocal determinism to analyze the effect of the online transition on students' teamwork, it is apparent that the three factors interacted and influenced one another. In response to the need to adapt their engineering lessons for online delivery (*environmental factor*), some students established new communication protocols (*behavioral factor*), which improved their ability to function as a team and carry out their lessons (*environmental factor*). As a result, students felt more satisfied with the project and their learning (*personal factor*). On the other hand, some team members reduced their participation in the project after the online transition (*behavioral factor*). This created an added burden on their teammates (*environmental factor*). Teammates typically responded by assuming new responsibilities (*behavioral factor*), thereby increasing their workload (*environmental factor*), which resulted in both positive (e.g., enhanced confidence, resilience) and negative (e.g., stress, frustration) personal outcomes (*personal factor*).

6.2. Student Learning from Online Team Experience

The transition to online learning affected what the students believed they learned from the project and from their team interactions specifically. Students noted acquiring professional skills such as leadership, teamwork, and effective team communication strategies as a result of their project experiences, and they acknowledged the project's utility for their future careers. They saw the benefits of cultivating talent and learning how to interact effectively with their team members. For example, a PST in C3 shared that, "due to [a result of leadership changes in her team following the shift to the virtual environment], I think I can now start to take more leader roles in group projects and work well with others without fearing judgment." PSTs and engineering students alike expressed how the project promoted flexibility, resilience, and persistence in professional tasks. C2 students gained valuable experience communicating virtually with parents and teammates, practices they are likely to utilize in their future careers.

Although traditional college-age students in 2020 frequently utilized digital communication tools for personal use, most did not know how to use virtual communication platforms for professional use [34]. Team members with technical prowess were valued and often assumed leadership roles. Thus, many students saw the value in these skills and perceived benefits from learning to use tools to collaborate online. For example, in C2, an engineering student explained:

> *"I think that having to use Zoom to carry out the remainder of this project is beneficial to my preparation for becoming an engineer. Virtual meetings are becoming more standard for many businesses and corporations, and I feel that being able to effectively communicate ideas and information in this manner will become invaluable."*

A few teams successfully completed their lessons as a group of autonomous workers with delegated tasks rather than as a true team that makes decisions collaboratively. Some of these students reported that this arrangement reduced their opportunity to learn from their teammates. This was the case for an engineering student in C1 who described his experience during his focus group:

> *"We had the same primary roles [after the transition]. However, in the [in-person] rehearsal, we were able to build on each other throughout each slide. Doing this conveyed us more as a team and I don't think we captured that same feeling on the online lesson. [. . .] I felt that moving to a virtual lesson affected me negatively. I found that I learned less from moving to online because we didn't get to work together with our teammates as much."*

Many students expressed similar negative experiences as a result of dividing tasks amongst teammates after the online transition. This created a disjointed experience where the benefits of collaboration were diminished. Students who reported less confidence in their skills seemed particularly vulnerable to this effect, whereas more confident students seemed able to absorb defunct partners' roles and move forward. While the interactions of most teams' interactions were not negatively influenced by the online transition, and few teams had negative environments, when there was a negative team dynamic, it was often found to lead to a disappointing learning experience overall for the affected students.

Applying Bandura's SCT lens, it is again apparent how the change in students' team environments both directly and indirectly impacted students' learning regarding teamwork. The team environments also impacted students' satisfaction with their team interactions and, as a result, affected their perceptions of the value of the project as a whole. Figure 3 illustrates how changes in team communication impacted students' environmental, personal, and behavioral factors. A common pathway of influence was for students' perceptions of their team context to prompt them to change their behavior, which then resulted in a personal impact. For example, after realizing that her engineering partner was not going to assist her in the manner originally planned (*environmental factor*), a PST adapted to teaching coding on her own (*behavioral factor*) and gained confidence (*personal factor*) as a result.

Students' personal factors (e.g., self-efficacy, COVID-related anxieties/events, and motivation for the project) also influenced these pathways. For example, a PST with low confidence in engineering (*personal factor*) grew very frustrated (*personal factor*) as she struggled to teach her 5th grader (*behavioral factor*) because her engineering partner was not actively participating (*environmental factor*). Eventually, a faculty member stepped in to assist. In another example, two grade-motivated college students chose to complete their lesson independently (*behavioral factor*) when their unproductive teammates had to unexpectedly drop the course due to COVID-19 implications (*environmental factor*).

Reciprocal interactions between factors were also apparent: when team members changed their behaviors, it changed the team environment. For example, team members who instituted new meeting protocols (*behavioral factor*) reported better team dynamics (*environmental factor*). Other environmental factors, such as feedback from faculty, also influenced team behaviors, such as prompting team members to make additional adaptations to their lessons (*behavioral factor*). As a PST in C3 described, "We changed everything related to feedback. When we got the instructor's feedback, my entire group got on a group call and worked on all of the recommendations until we completed them all."

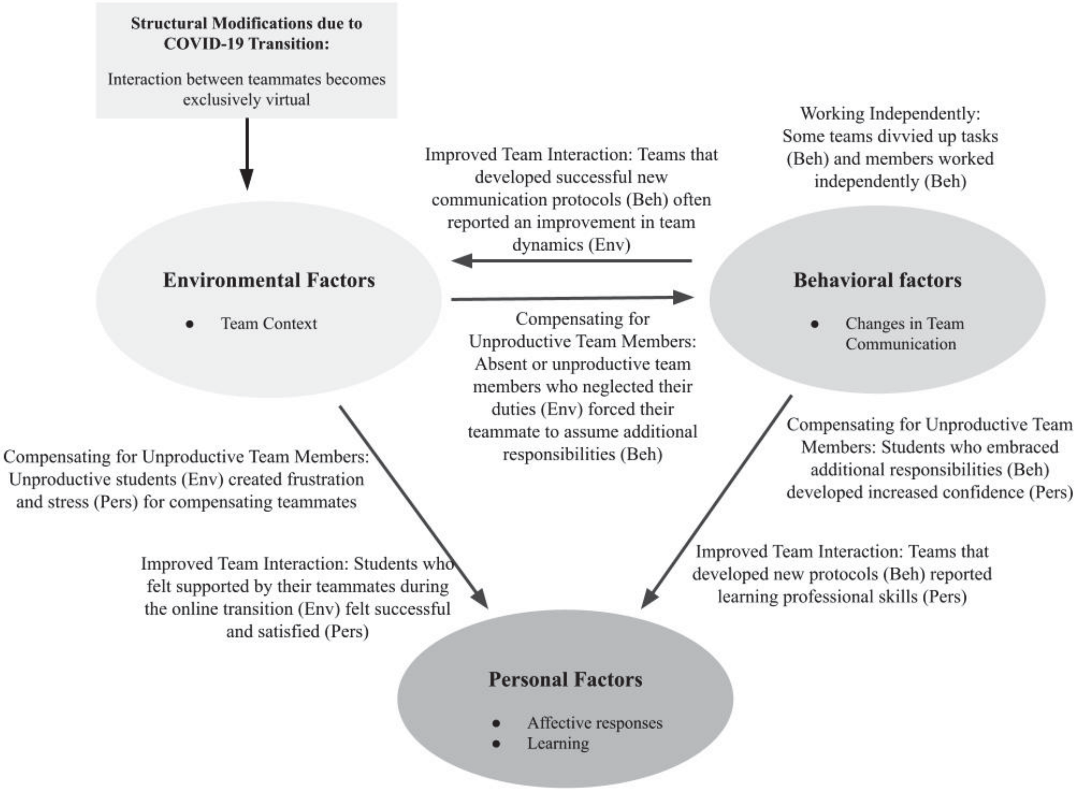


Figure 3. The Influence of Modified Team Interaction (i.e., Moving from Face-to-Face to Virtual Communication) Depicted within Bandura's Triadic Model of Reciprocal Determinism. *Note.* This figure illustrates how environmental (Env), behavioral (Beh) and personal factors (Pers) interact to influence student functioning via examples of commonly reported perceptions. The arrows indicate commonly observed pathways of influence between the factors.

7. Discussion

Bandura's social cognitive theory sheds light on the way the transition to online learning following the onset of the COVID-19 pandemic shaped students' experiences, both directly, by modifying the environment in which they learned and collaborated, and indirectly, through the change in the project goal imposed by the instructors. An examination of the environmental factors of the Spring 2020 semester made it clear that students were responding to a multitude of simultaneous changes: a change in their learning environment, a change in the modality through which they collaborated with peers, and a change in the media they used to deliver instruction. Student experiences were influenced by these environmental factors at both the team and individual levels, and these dynamics were reciprocal so that students both influenced and were influenced by their teams. The students' experiences adapting to these environmental changes can provide insight for all educators, including those involved in teacher and engineer preparation programs, as they consider the best ways to support students engaged in teamwork and develop course assignments beneficial for student learning and professional development. The findings from the current study corroborate and add to the conclusions made by Kilty and Burrows [25] as they examined factors contributing to effective teams in informal settings through integrated STEM partnerships. The concluding sections outline some of the ways in which the current study found that successful partnerships can be established, many of which align closely with prior teamwork and partnership literature [25,35].

While all teams were ultimately successful in that they produced an artifact that met the objectives of their course, some teams reported a more seamless adjustment to their new environmental conditions than others. Several lessons regarding teamwork can be drawn from the experiences of students within their teams. Teams that were able to successfully adapt to their new environmental conditions reported several strategies that helped them succeed: maintaining roles and routines established early in the semester but taking time to meet more frequently if needed; taking time to establish a common understanding of their new task, especially prior to delegating tasks; and using synchronous communication tools that facilitate richer communication. Satisfied teams also found ways to persist despite unresponsive team members.

These findings can help educators plan effective strategies to support teamwork. One such strategy is a practice adopted by the research team several years ago that has proven beneficial for supporting student teamwork even through modifications made mid-pandemic—having students create and sign a team charter. This practice helps team members establish accountability and align expectations regarding the task and create a shared vision of their team plan [36]. Teams in this study also reported being able to establish communication protocols and roles prior to the online transition and being able to maintain these through the online transition. In fully online courses, when students are more likely to feel disconnected [37,38], instructors should help teams develop social structures and communication patterns to accomplish their goals [11].

Another strategy is to promote the use of synchronous communication tools for teams, especially teams that are not able to meet face-to-face. Face-to-face interaction, especially during the early stages of team projects, has been found to be more conducive to establishing trust than meeting virtually [27,28]. Teams in this study had the advantage of meeting in-person during the early weeks of the semester, which may have helped them establish bonds. Undergraduate students who are collaborating virtually and who are unlikely to have significant teamwork experience may be tempted to forgo synchronous meetings and use texting as their primary means of team communication. Instructors would be wise to impose guidelines that require teams to meet synchronously to help establish rapport, especially during the early stages of the projects and for complex and ambiguous tasks. The teams in this study also shared the importance of meeting the needs of their clients, the elementary students. Teams in Collaborations 2 and 3 who were able to meet with their assigned elementary students in either a face-to-face or synchronous format prior to and/or during the school shutdowns shared how valuable those meetings were. This finding aligns with that of Ng [39], where he writes that while students were able to adapt to the rapid transition to online learning, they preferred a hybrid approach where face-to-face interactions allowed them to have "contact and social interactions" [4] (p. 438).

The rapid transition to online teaching and learning was overwhelming to educators and students throughout all grade levels, K-20 [5,6]. Asking elementary teachers to teach the engineering lessons synchronously or distribute the lessons asynchronously for students was perceived as just 'one more thing,' they had to deal with during an already very difficult transition to online learning, and proved to be too great of an additional burden. Accordingly, few elementary students were exposed to the engineering lessons produced. Meanwhile, at the college level, other COVID-related studies found that personal factors for students' learning, such as a lack of self-regulation or independent learning skills, may have made it increasingly difficult for students to be successful in online learning environments [3,5]. Jeffries et al. [3] also acknowledged the mental health concerns for students that may have been "compounded by isolation and lack of connection to instructors and peers" (p. S105).

On the positive side, in the current study in Spring 2020, when stress from COVID-19 was running high, some students found emotional support from their teammates. Prior research has found associations between students' sense of inclusion in a team and their motivation [40,41]. Instructors who want to leverage motivational benefits from team projects may want to consider team building activities that help support team bonding and performance [42,43]. Underproductive team members are a common occurrence in team projects, even outside of semesters affected by COVID-19 [44]. Instructors that require students to prepare for such an eventuality may be less likely to have to deal with fallout later on [45,46]. The COVID-19 pandemic resulted in disruptions that could not have been anticipated. Adequately preparing teams for potential disruptions can help students have successful team experiences regardless of what obstacles appear in their paths.

8. Limitations

As with all studies, there are limitations associated with the current study. First, our study is limited by its particular context. The students' experiences were tied to their participation in an NSF-funded cross-disciplinary service-learning project that involved undergraduate education and engineering students. We cannot assume that college students engaged in team-based projects within a single discipline or across two different disciplines or in the context of a project that was not focused on providing a service to elementary students, would have similar outcomes. The unique and specific context of our project is both an asset and a limitation. It is an asset because it provides a model for how engineering instruction can be delivered online to children in a way that also benefits education and engineering students' professional development, but it is a limitation in that there are many components of this project that could be contributing to the outcomes we witnessed, and it would be nearly impossible to isolate the exact driving forces behind the outcomes we observed. Furthermore, the participants' experiences reflected in this study were collected during a semester that was heavily influenced by COVID. The pandemic created a unique opportunity to study team interactions and draw conclusions and lessons that are meaningful even outside of the COVID-19 context.

Secondly, the complexity of the three factors (i.e., environmental, personal, and behavioral) that comprise Social Cognitive Theory makes it challenging to identify any and all interactions among the factors for any given participant's experience. The social, behavioral, and environmental factors that influenced the students' experiences did so in concert with one another, and although we did our best to identify connections between individual factors, there is no guarantee that a unique combination of influences, rather than a single influence, was not critical in fostering a given outcome. Finally, qualitative analysis provides rich explanations of participants' perceived experiences and is even able to begin identifying causal relationships and explanations in and among the three factors. However, the degree to which these relationships influence or cause one another cannot be answered through the qualitative data examined in this study.

9. Conclusions & Implications

SCT was used as a lens to illuminate the participating education and engineering students' experiences of transitioning to an online environment. The triadic model of reciprocal determinism helped illustrate the relationships among students' environmental, personal, and behavioral factors as they collaborated to develop online engineering lessons for elementary students. Not only can these findings be used to inform other, similar, team-based projects in engineering education that utilize online instruction, but they can also be applied more broadly to help explain the processes by which students' attitudes and beliefs about engineering integration change as a result of environmental modifications.

It has been argued that "once the pandemic is over, [. . .] new knowledge, skills, technologies, and innovations will remain" [3] (p. S104). The current study examined how the environmental, personal, and behavioral factors associated with rapid changes in university students' teamwork experiences impacted students' knowledge and skills and innovative ways of using technologies to collaborate. Results suggest that the transition to online learning did not significantly disrupt the education and engineering students' ability to collaborate in the development of an elementary-level engineering lesson. Every team rose to the challenge of adapting their lesson for online delivery and produced either a final slideshow that was shared with teachers or delivered a lesson synchronously and directly to elementary school students. The implication of the findings from this study suggests that with the right resources and support, hands-on engineering instruction can be carried out effectively online, even by novices. Additionally, students experienced many challenges while collaborating with their peers to develop online lessons but reported learning new skills and appreciating the opportunity to teach and communicate online, while mostly enjoying their experiences. This project provided these undergraduates with the opportunities to enhance their professional skills, such as communication, collaboration, self-efficacy, and digital skills, many of which were emphasized as areas of needed growth for higher education students in the articles highlighted by O'Dea and Stern [4]. Therefore, while this study is limited to the unique context of pandemic-induced online settings, it sheds light on online engineering education in that future generations can develop their professional skills and effectively teach engineering in online settings.

Future work stemming from this study includes an exploration of the factors that motivated undergraduate students in the project. Thus far, our work is inconclusive regarding the degree to which specific aspects of the project (e.g., interaction with elementary students (clients), commitment to team success, grades, etc.) motivated individual students. Additionally, the project team would like to examine how this interdisciplinary team model influences the development of students' self-efficacy, particularly the pre-service teachers, in teaching engineering to elementary students. Finally, as other scholars have noted (e.g., [3,4]), there is a need for continued examination and evaluation of the best practices in online teaching and learning, particularly in the area of long-term effectiveness.

This interdisciplinary partnership provided pre-service teachers and undergraduate engineering students with the opportunity to develop the teamwork skills they will need in future working environments. It helped students test their ability to work in an online environment, informing them whether they are ready to collaborate effectively remotely, or if they still need more development with that particular skill set. The shift to online learning and teaching in the Ed+gineering project has helped prepare engineering students and pre-service teachers for the increasingly global context of today's professional environments where effective virtual communication is essential.

Author Contributions: Conceptualization, K.S.G., J.J.K. and M.J.L.; Methodology, K.S.G., J.J.K. and M.J.L.; Software, n/a; Validation, K.S.G., J.J.K. and M.J.L.; Formal Analysis, K.S.G., J.J.K. and M.J.L.; Investigation, J.J.K., K.S.G., S.I.R., P.P., O.A., K.K. and M.J.L.; Resources, J.J.K., K.S.G., S.I.R., P.P., O.A. and K.K.; Data Curation, K.S.G., J.J.K. and M.J.L.; Writing—Original Draft Preparation, K.S.G., J.J.K., M.J.L. and P.P.; Writing—Review & Editing, K.S.G., J.J.K., M.J.L., P.P., S.I.R., O.A. and K.K.; Visualization, K.S.G., J.J.K. and M.J.L.; Supervision, K.S.G.; Project Administration, J.J.K.; Funding Acquisition, J.J.K., K.S.G., S.I.R., P.P., O.A. and K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This material is based upon work supported by the National Science Foundation under Grant Nos. 1908743 and 1821658. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Old Dominion University (protocol codes 1249767-12; 1451315-17 and 21 August 2018; 13 September 2019).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The project team would like to acknowledge the hard work and dedication of our undergraduate students and teaching assistants who participated in this project, especially during the onset of a global pandemic. Additionally, we would like to thank the elementary teachers and elementary students who interacted with our college students and the uniquely designed materials created especially for them!

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bourne, J.; Harris, D.; Mayadas, F. Online Engineering Education: Learning Anywhere, Anytime. *J. Eng. Educ.* **2005**, *94*, 131–146. [CrossRef]
2. García Aretio, L. COVID-19 and digital distance education: Pre-confinement, confinement and post-confinement. *RIED Rev. Iberoam. Educ. Distancia* **2021**, *24*, 09–32. [CrossRef]
3. Jeffries, P.R.; Bushardt, R.L.; DuBose-Morris, R.; Hood, C.; Kardong-Edgren, S.; Pintz, C.; Posey, L.; Sikka, N. The Role of Technology in Health Professions Education During the COVID-19 Pandemic. *Acad. Med. J. Assoc. Am. Med. Coll.* **2022**, *97*, S104–S109. [CrossRef] [PubMed]
4. O'Dea, X.; Stern, J. Virtually the same?: Online higher education in the post COVID-19 era. *Br. J. Educ. Technol.* **2022**, *53*, 437–442. [CrossRef] [PubMed]
5. Pérez López, E.; Vázquez Atochero, A.; Cambero Rivero, S. Distance Educ. in COVID-19′s Period: An Analysis from the Perspective of University Students. *RIED Rev. Iberoam. Educ. Distancia* **2021**, *24*, 331–350. [CrossRef]
6. Roig-Vila, R.; Urrea-Solano, M.; Merma-Molina, G. Communication at University Classrooms in the Context of COVID-19 by Means of Videoconferencing with Google Meet. *RIED Rev. Iberoam. Educ. Distancia* **2021**, *24*, 197–220. [CrossRef]
7. Barr, M.; Nabir, S.W.; Somerville, D. Online Delivery of Intensive Software Engineering Education During the COVID-19 Pandemic. In Proceedings of the 2020 IEEE 32nd Conference on Software Engineering Education and Training (CSEE&T), Munich, Germany, 9–12 November 2020.
8. Asgari, S.; Trajkovic, J.; Rahmani, M.; Zhang, W.; Lo, R.C.; Sciortino, A. An observational study of engineering online education during the COVID-19 pandemic. *PLoS ONE* **2021**, *16*, e0250041. [CrossRef]
9. Rassudov, L.; Korunets, A. COVID-19 Pandemic Challenges for Engineering Education. In Proceedings of the 2020 XI International Conference on Electrical Power Drive Systems (ICEPDS), St. Petersburg, Russia, 4–7 October 2020. [CrossRef]
10. Andel, S.A.; de Vreede, T.; Spector, P.E.; Padmanabhan, B.; Singh, V.K.; de Vreede, G.-J. Do social features help in video-centric online learning platforms? A social presence perspective. *Comput. Hum. Behav.* **2020**, *113*, 106505. [CrossRef]
11. Van Tryona, P.J.S.; Bishop, M.J. Theoretical foundations for enhancing social connectedness in online learning environments. *Distance Educ.* **2009**, *30*, 291–315. [CrossRef]
12. Vielma, K.; Brey, E.M. Using Evaluative Data to Assess Virtual Learning Experiences for Students During COVID-19. *Biomed. Eng. Educ.* **2020**, *1*, 139–144. [CrossRef]
13. Francescucci, A.; Rohani, L. Exclusively Synchronous Online (VIRI) Learning: The Impact on Student Performance and Engagement Outcomes. *J. Mark. Educ.* **2019**, *41*, 60–69. [CrossRef]
14. Gutierrez, K.; Kidd, J.; Lee, M. It's virtually possible: Rethinking preservice teachers' field experiences in the age of COVID-19 and beyond. In *What Teacher Educators Should Have Learned from 2020*; Ferdig, R.E., Pytash, K., Eds.; Association for the Advancement of Computing in Education (AACE): Waynesville, NC, USA, 2021; pp. 169–181.
15. Pazos, P.; Ringleb, S.I.; Kidd, J.; Jones, R. Scaffolding Project-Based Learning in an Engineering and Education Partnership using Open-Access Technology. *Int. J. Eng. Educ.* **2019**, *35*, 1306–1315.
16. Park, H.-R.; Kim, C.-J.; Park, J.-W.; Park, E. Effects of team-based learning on perceived teamwork and academic performance in a health assessment subject. *Collegian* **2015**, *22*, 299–305. [CrossRef]
17. Vogler, J.S.; Thompson, P.; Davis, D.W.; Mayfield, B.E.; Finley, P.M.; Yasseri, D. The hard work of soft skills: Augmenting the project-based learning experience with interdisciplinary teamwork. *Instr. Sci.* **2018**, *46*, 457–488. [CrossRef]
18. Ritter, B.A.; Small, E.E.; Mortimer, J.W.; Doll, J.L. Designing management curriculum for workplace readiness: Developing students' soft skills. *J. Manag. Educ.* **2018**, *42*, 80–103. [CrossRef]
19. Halfhill, T.R.; Nielsen, T.M. Quantifying the "softer side" of management education: An example using teamwork competencies. *J. Manag. Educ.* **2007**, *31*, 64–80. [CrossRef]
20. Pazos, P.; Magpili, N.; Zhou, Z.; Rodriguez, L.J. Developing Critical Collaboration Skills in Engineering Students: Results from an Empirical Study. In Proceedings of the American Society for Engineering Education Annual Conference Proceedings, New Orleans, LA, USA, 26–29 June 2016. [CrossRef]
21. Passow, H.J. Which ABET competencies do engineering graduates find most important in their work? *J. Eng. Educ.* **2012**, *101*, 95–118. [CrossRef]
22. Shuman, L.J.; Besterfield-Sacre, M.; McGourty, J. The ABET "Professional skills"—Can they be taught? Can they be assessed? *J. Eng. Educ.* **2005**, *94*, 41–55. [CrossRef]
23. Barker, R.T.; Gilbreath, G.H.; Stone, W.S. The interdisciplinary needs of organizations: Are new employees adequately equipped? *J. Manag. Dev.* **1998**, *17*, 219–232. [CrossRef]

24. Dare, E.A.; Keratithamkul, K.; Hiwatig, B.M.; Li, F. Beyond Content: The Role of STEM Disciplines, Real-World Problems, 21st Century Skills, and STEM Careers within Science Teachers' Conceptions of Integrated STEM Education. *Educ. Sci.* **2021**, *11*, 737. [CrossRef]
25. Kilty, T.J.; Burrows, A.C. Integrated STEM and Partnerships: What to Do for More Effective Teams in Informal Settings. *Educ. Sci.* **2022**, *12*, 58. [CrossRef]
26. Walther, J.B. Computer-Mediated Communication: Impersonal, Interpersonal, and Hyperpersonal Interaction. *Commun. Res.* **1996**, *23*, 3–43. [CrossRef]
27. Crisp, C.B.; Jarvenpaa, S.L. Swift Trust in Global Virtual Teams: Trusting Beliefs and Normative Actions. *J. Pers. Psychol.* **2013**, *12*, 45–56. [CrossRef]
28. Jarvenpaa, S.L.; Leidner, D.E. Communication and Trust in Global Virtual Teams. *Organ. Sci.* **1999**, *10*, 25. [CrossRef]
29. Wilson, J.M.; Straus, S.G.; McEvily, B. All in due time: The development of trust in computer-mediated and face-to-face teams. *Organ. Behav. Hum. Decis. Processes* **2006**, *99*, 16–33. [CrossRef]
30. Bandura, A. *Social Foundations of Thought and Action: A Social Cognitive Theory*; Prentice-Hall, Inc.: Englewood Cliffs, NJ, USA, 1986.
31. Bandura, A. *Social Cognitive Theory*; JAI Press: Greenwich, CT, USA, 1989.
32. Schunk, D.H.; DiBenedetto, M.K. Motivation and social cognitive theory. *Contemp. Educ. Psychol.* **2020**, *60*, 101832. [CrossRef]
33. Rourke, L.; Anderson, T. Validity in quantitative content analysis. *Educ. Technol. Res. Dev.* **2004**, *52*, 5–18. [CrossRef]
34. Smith, E.E.; Kahlke, R.; Judd, T. Not just digital natives: Integrating technologies in professional education contexts. *Australas. J. Educ. Technol.* **2020**, *36*, 1–14. [CrossRef]
35. Mullinix, B.B. Nurturing Partnership: A Southern African Continuum of Flexible Stages in Partnership Development. *Curr. Issues Comp. Educ.* **2002**, *3*, 77–88. Available online: https://www.tc.columbia.edu/cice/pdf/25681_3_2_Mullinix.pdf (accessed on 20 May 2022).
36. Pazos, P.; Cima, F.; Kidd, J.; Ringleb, S.I.; Ayala, O.; Gutierrez, K.S.; Kaipa, K. Enhancing teamwork skills through an engineering service learning collaboration. In Proceedings of the American Society for Engineering Education Annual Conference Proceedings, Online, 22–26 June 2020. [CrossRef]
37. Menchaca, M.P.; Bekele, T.A. Learner and instructor identified success factors in distance education. *Distance Educ.* **2008**, *29*, 231–252. [CrossRef]
38. Reisetter, M.; Boris, G. What Works: Student Perceptions of Effective Elements in Online Learning. *Q. Rev. Distance Educ.* **2004**, *5*, 277–291.
39. Ng, D.T.K. Online aviation learning experience during the COVID-19 pandemic in Hong Kong and Mainland China. *Brit. J. Educ. Tech.* **2022**, *53*, 443–474. [CrossRef]
40. Bidee, J.; Vantilborgh, T.; Pepermans, R.; Willems, J.; Jegers, M.; Hofmans, J. Daily motivation of volunteers in healthcare organizations: Relating team inclusion and intrinsic motivation using self-determination theory. *Eur. J. Work. Organ. Psychol.* **2017**, *26*, 325–336. [CrossRef]
41. Stults-Kolehmainen, M.A.; Gilson, T.A.; Abolt, C.J. Feelings of acceptance and intimacy among teammates predict motivation in intercollegiate sport. *J. Sport Behav.* **2013**, 36.
42. Delson, N.J. Increasing team motivation in engineering design courses. *Int. J. Eng. Educ.* **2001**, *17*, 359–366.
43. Klein, C.; DiazGranados, D.; Salas, E.; Le, H.; Burke, C.S.; Lyons, R.; Goodwin, G.F. Does team building work? *Small Group Res.* **2009**, *40*, 181–222. [CrossRef]
44. Wolfe, J.; Powell, E.A.; Schlisserman, S.; Kirshon, A. Teamwork in engineering undergraduate classes: What problems do students experience? In Proceedings of the 2016 ASEE Annual Conference & Exposition, New Orleans, LA, USA, 26 June–28 August 2016. [CrossRef]
45. Long, J.; Rajabzadeh, A.R.; MacKenzie, A. Teaching teamwork to engineering technology students: The importance of self-reflection and acknowledging diversity in teams. *Proc. Can. Eng. Educ. Assoc.* **2017**, *37*, 1–7. [CrossRef]
46. Wolfe, J.; Powell, E. Strategies for dealing with slacker and underperforming teammates in class projects. In Proceedings of the 2014 IEEE International Professional Communication Conference (IPCC), Pittsburgh, PA, USA, 13–15 October 2014. [CrossRef]

education sciences

MDPI

Article

Integrated STEM and Partnerships: What to Do for More Effective Teams in Informal Settings

Trina J. Kilty [1,*] and Andrea C. Burrows [2]

[1] Department of Computer Science, University of Wyoming, Laramie, WY 82071, USA
[2] School of Teacher Education, University of Wyoming, Laramie, WY 82071, USA; andrea.burrows@uwyo.edu
* Correspondence: tkilty@uwyo.edu

Abstract: The purpose of this study was to explore how undergraduate college students formed partnerships in informal educational teams to design and build an interdisciplinary, ill-defined, integrated science, technology, engineering, and mathematics (STEM) project and translate it to lessons taught to a pre-collegiate student (e.g., K-12 in the US) audience. The authors pursued two research questions: (a) How does an authentic research project provide space for integrating STEM disciplines? (b) How does an authentic research project impact partnerships among team members? Nine undergraduate college students were accepted into the 2020 cohort, forming three teams of three undergraduates each. Teams were roughly composed of one engineering major, one science major, and one education major. Methods of data collection included interviews and field notes. Data were analyzed by assessing the level of partnership achieved based on an already established model. Results indicate that all teams progressed through pre-partnership to at least the partnership (little p) level. Two partnership dimensions achieved the highest (big P) level: one of perception of benefit and one of products and activities. The results have implications that integration of STEM disciplines and forming partnerships could be related, and that building teamwork skills results in products of higher quality. The results are linked to previous research and recommendations for more effective partnerships are provided.

Keywords: integrated STEM; partnerships; interdisciplinary teams; informal education; team building; real-world problems; authentic science; effective collaboration; partnership dimensions

Citation: Kilty, T.J.; Burrows, A.C. Integrated STEM and Partnerships: What to Do for More Effective Teams in Informal Settings. *Educ. Sci.* **2022**, *12*, 58. https://doi.org/10.3390/educsci12010058

Academic Editors: Mieke De Cock and Billy Wong

Received: 21 October 2021
Accepted: 11 January 2022
Published: 17 January 2022

1. Introduction

There is a nationwide call throughout the United States and the world for integrating the disciplines of science, technology, engineering, and mathematics (STEM) to prepare students for needed 21st-century skills [1,2]. Researchers have identified necessary core skills including effective communication, collaboration, problem solving, critical thinking, and creativity, along with technical skills and information management [3]. Some researchers claim that these skills are equally essential [4]. To achieve these skills, teachers may integrate the STEM disciplines, and one way is implementing engineering design principles in different contexts that emphasize underlying crosscutting concepts [5]. The authors of this study were inspired to develop and implement an undergraduate college student research project using an authentic setting and bringing together undergraduates from engineering, science, and education majors and disciplines, as those projects have been successful in the past [6]. The authors were interested in exploring how a context favoring integrated STEM might impact undergraduate college students to form a team and work in partnership toward designing and building a quality product.

The grant-funded internship project was implemented for the duration of three calendar years. During the second year, 2020, the authors designed and carried out a study to explore how undergraduate college students formed partnerships through teamwork to design and build an interdisciplinary, ill-defined, integrated STEM project (taking place outside of college coursework) and translate their project to lessons taught to a pre-collegiate student (e.g., K-12) audience. The authors utilized the idea that "encouraging design teams to monitor their activities can be beneficial" [7] p. 623. Many researchers have explored teaming; however, many of these studies are conducted outside of the educational setting [3,8–17]. Seeking understanding in an educational setting, but in a non-traditional learning space, the authors pursued the following research questions: (a) How does an authentic research project provide space for integrating STEM disciplines? (b) How does an authentic research project impact partnerships among team members?

1.1. Theoretical Framework and Background Literature

The authors conceptualized the overall project according to themes of authentic scientific inquiry, problem-based learning, integration of STEM disciplines, hands-on learning, and emphasis on engineering design practices, as components of integrated STEM learning [18]. The authors used problem-based learning [19], described by Merrit and others [20] as solving problems by integration and application of knowledge in actual settings and similar to clinical or medicine education. The authors encouraged utilization of engineering design practices as a model for this qualitative case study. The authors asked undergraduate college students to build and teach in authentic pre-collegiate school settings, and both of these components align with authentic scientific inquiry [21]. The projects were ill-defined problems the participants chose together as a team. The authors placed undergraduates in teams to encourage teamwork, an implied definition of such reported by Newell and Bain [22] to include higher education students, interdisciplinary, focus on the process, using problem-based learning, of developing interpersonal skills and partnerships [22]. The undergraduate teams needed to conduct research to determine if their problem and proposed solution was feasible, how to plan and carry out an experiment to collect data, and how to translate their work to a younger, less-technical audience. The undergraduates taught lessons as outreach with a partnering local school.

The theoretical framework utilized was an interpretivist, hermeneutics lens. The authors purposely attempted to understand participants' experiences, and to interpret the phenomenon of the authentic STEM project and partnership development. The research questions that ask "how" the project integrates with disciplines and impacts partnerships are in line with a hermeneutics framework. In this case study, where the participants were all tasked with the same problem, the participants were interviewed as well as observed, and the participant was the main producer of knowledge. The authors' role was to describe what they heard and saw as detached researchers [23].

1.1.1. Integrated STEM

For the authors of this article, and informed by multiple authors [24], STEM integration is defined as a space where STEM problems are from the real-world, connected by concepts and skillsets, have multiple disciplines represented, provide structure for the integration, and offer a space for participant collaboration. The nine undergraduate college students in this study, comprised three teams of three members each. The three projects required the undergraduates to stretch beyond the comfort zone of their major of study to learn new skills and knowledge from other disciplines. The completion of the project asked students to utilize engineering design practices, which non-engineering majors may have been unfamiliar with but have been implemented as part of national science standards in many pre-collegiate schools [5]. Possibilities for integration of disciplines were involved with formulating a real-world scientific question or an engineering problem that could be addressed by gathering data associated with a high-altitude balloon, designing and building a payload project to accompany a high-altitude balloon, collect and analyze data attached to sensors on a high-altitude balloon answering the question or solving the problem, and finally, to translate the project into lessons for informal outreach to a pre-collegiate audience. To accomplish this, the undergraduates worked with a partnering teacher at a participating pre-collegiate (e.g., K-12) school. This integration and emphasis on interconnectedness involved STEM majors working with education majors, some of whom intended to teach in a non-STEM discipline (e.g., English).

The authors conceptualized the participants working as teams on the project according to integration of STEM disciplines, with emphasis on engineering design practices [18]. The authors tried to place projects in the context of authenticity [21] as well as emphasizing engineering design practices [25,26]. Overall, the undergraduate teams used a modified collaborative and cooperative learning approach, which has been shown to increase meaningful learning in a social environment [27]. A true cooperative learning strategy encourages interdependence among team members, which we encouraged, but lacked structure and teacher direction [28], given that this study took place outside of formal undergraduate coursework. The authors followed the collaborative learning model as defined by van Leeuwen and Janssen [29] more closely than they did the cooperative learning model, by encouraging the undergraduate team members to coordinate effort to successfully complete the project, which aligned well with integrated STEM. Researchers may use collaborative and cooperative learning interchangeably [20,29], while others define the concept broadly to mean any setting in which more than two people come together to learn something [30] to include learning in online settings [31].

The authors used a design like other studies exploring how preservice teachers integrate STEM and followed recommendations to modify for strategic, purposeful partnerships, a focus on how the project applies to real life, encourage reflection on prior experience of teaching and learning, and use online resources to conduct background research [32]. The authors of this study followed other’s recommendations to allow the undergraduates time for maximum exploration and choice of project during the initial stages as well as to encourage iteration and monitor perceptions of team dynamics [7].

The undergraduates were expected to design and develop an experiment product, hereafter referred to as a payload, that would collect data necessary to answer their real-world question or solve their problem. This utilized a problem-based learning strategy that asks learners to pursue knowledge germane to solving the problem. Researchers have found that educational activities utilizing problem-based learning have resulted in learning gains [25], creativity [33], lateral thinking [34], and one twenty-year meta-analysis of project-based learning showed medium to large mean effect size (0.71) for student achievement [35]. Problem-based learning has a constructivist context, and one of the six aspects researchers have described is that going through the process results in participants seeing value in interdisciplinary teamwork and accepting the challenges in working with different perspectives [36]. Moreover, other researchers have found that problem-based learning contributes to teamwork, communication, and time management [13]. The conversation is ongoing, but still supported, as some researchers have proposed moving from problem-based learning (and the prior project-based learning) to practice-based education [37].

For this study, the authors provided undergraduates a choice of project, but purposefully formed teams based on intended major of study. The teams were encouraged to make the project community-based, culturally relevant, collaborative, engaging, and representative of all the STEM disciplines. The authors studied the teams’ process leading to performance in the sense of creating a payload and teaching lessons to a younger audience. Both mental models and team interactions, insofar as their knowledge gleaned from their major area of study, constitute a teamwork process [15]. Although the projects in 2020 aligned with personal interests of the participants, there was a greater societal impact to all projects. The partnering pre-collegiate teacher helped tailor projects to provide place-based and locally relevant context for lessons at the local school. Moreover, the authors guided the undergraduates to select projects that would apply their coursework to an actual problem, the real world, and what they might do in their future career.

Each team conducted a background study to choose their project query, in terms of a problem to solve or a question to answer by collecting data attached to sensors on a high-altitude balloon and translate their learning to lessons they taught to a younger audience. Although this overall goal was stated upfront by leadership and time on task was clearly outlined, intermediate goals of test launch, writing lesson plans, and planning classroom visits were decided by the undergraduate teams. Thus, teams set their own intermediate goals with the ultimate goals of completion of the project. Some researchers have shown that the most difficult goals lead to the highest effort and performance [12]. Setting goals that direct effort in a relevant way may energize team members and lead to action and persistence [12]. This goal setting theory was the foundation of the authors allowing undergraduate teams free rein to choose project questions, develop a payload, communicate with the partner teacher, and plan and deliver lessons in a K12 classroom. In addition to the performance goals of payload data collection and delivery of classroom lessons, the authors recommended that the undergraduates set goals as well, because research has shown the even the perception of others' mastery goals has a positive effect on a team's overall engagement and motivation [11].

1.1.2. Partnerships

As recommended [18], the authors encouraged "transfer knowledge across disciplines" by purposefully forming diverse teams. The project team spent time considering "the [informal] environment where the activities [would] take place, time allotment, facilitator background and availability, and the [grant's] overarching goals" [38] p. 44, which are important factors to consider when creating a non-traditional learning environment. The authors, following recommendations by researchers, did not designate a leader, allowing students to organically develop a leader—or not, as researchers have shown that there is no measurable difference unless there is a time constraint [17]. Each team included one engineering major, one science major, and one preservice teacher education major. The teams were asked over the course of a calendar year to build a real-world experiment, a device that collected data, or payload, that was attached to sensors on a high-altitude balloon launched at the participating pre-collegiate school. The project provided real-world experience for the preservice teacher by packaging lessons and activities and teaching them as informal outreach to a local classroom.

By deliberately creating this synergy, the authors were orchestrating a high level of integration [39] among undergraduate teams and aligning goals. Researchers have suggested that outcomes are better if team members' goals are aligned [9]. The authors purposefully formed undergraduate teams to foster teamwork and develop partnerships. Researchers showcased how discussions based on evidence-based justification for design decisions among middle school students were a key factor in fully integrating STEM disciplines [40]. Applications to the real-world extend to not only the problem chosen, but also to the teamwork (potentially forming partnerships) necessary in STEM disciplines as well as education. This style of collaborative learning through interaction has been shown to increase intrinsic motivation and satisfaction and will affect attitudes of participants [41]. Overall, evidence exists that communication is key to successful teamwork [8].

Working from this model, the authors designed a study to explore the intersection and interactions between integrated STEM projects and the development of partnerships among a team of undergraduates with different majors of study. STEM discipline cohesion is aided by coordination of tools and materials, forward and backward projection to reference when teaching, and use of consistent underlying concepts when teaching [42]. Conflicts, both micro and macro, were expected. Researchers have shown that micro conflicts are bound to happen, and the resulting interactions reduced uncertainty in successful teams and increased it in unsuccessful ones [16]. Educational researchers have proposed a definition of a team, "members' interdependent acts that convert inputs to outcomes, through cognitive, verbal, and behavioral activities directed toward organizing taskwork to achieve collective goals" [16] p. 357. The process of teamwork describes how a team is doing and the nature of member interaction [14]. These researchers propose the time span for a team be divided into episodes based on activity, thereby defining a period in which goals are set, another of action, and the third of interpersonal relationships [14]. In this sense, the team progresses towards the ultimate goal by moving in and out of episodes in which attention shifts towards one of these episodes. Because the study timeframe was open under the umbrella of a calendar year, the authors framed teamwork into episodes of goal setting, followed by payload work, followed by goal setting, followed by lesson planning. Action mainly happened in the final semester as payloads were launched and lessons taught.

The undergraduate teams based the projects themselves on integrated STEM content, drawing from all disciplines of STEM to an extent, as described in Table 1 and met the collaboration, skills, and structure pieces too. The authors designed the integrated nature of the projects to facilitate participants to learn from each other, gain appreciation of the integrated nature of STEM, and build a potentially partnership-based team.

Table 1. Description of team members and projects.

Team Members (Pseudonyms)	Major Area of Study	Project Description	STEM Integration
May (Female) Meg (Female) Mike (Male)	Science Education Mechanical Engineering Civil Engineering	**Microbes**: Collect microbes at high altitude	S = microbes background knowledge T = payload, high-altitude balloon E = design mechanism to collect data M = coding, programming Arduino (&T)
Gabe (Male) Glen (Male) Gail (Female)	Science Education Computer Engineering Physics	**GPS**: Measure occultation of GPS signal at high altitude	S = occultation and weather prediction T = program raspberry pi E = build payload M = works with T, coding, angles
Carla (Female) Carol (Female) Cal (Male)	English Education Mechanical Engineering Physics	**Cell Signal**: Determine nature of cell phone signals at high altitude	S = nature of cell signals T = payload, high-altitude balloon E = build payload, collect data M = interpret and display data as graph

2. Materials and Methods

The authors conceptualized this study as a qualitative, collective case study [43]. The case study was instrumental to refining understanding of how, in undergraduate teams, partnerships intersect with integrated STEM. The overall National Science Foundation grant-funded project spanned three calendar years, and the purpose was to address the issue of improving undergraduate STEM education. This study focused on the 2020 cohort according to three purposefully selected teams, which made cross analysis multiple case study possible by comparing each team, or case, with each other in the overall context of the collective case study [43,44]. The authors used an interpretivist, theoretical stance in this study to describe the undergraduates' experiences and meaning making during the process of forming partnerships and building teamwork [23]. Sources of data in this process-based study included interviews with each participant and observational field notes (taken by the authors) of the teams during weekly official meetings and during teaching in the pre-collegiate classroom. The field notes and transcribed interviews were coded and analyzed deductively according to the model of partnerships developed by Mullinix [45]. Triangulation of data collection, namely observations, interviews, and the products of the undergraduates' projects (e.g., experimental payload and lesson plans) ensured credibility. Credibility was also enhanced by discussion between the authors, and constant comparison of authors' interpretations of the data and the coding of partnership level [44]. Teams (cases) were analyzed within and comparatively [44] to further understanding of the research questions.

The authors asked the undergraduates to work from an engineering perspective (as described by [46]) as a construct of human-made test of a solution. The criteria were the practical success of the payload as a technical product that was effective and efficient at answering the question or solving the problem. The nuances of how teamwork functioned were perceived, constructed, and communicated by the participants to the authors. Although the authors considered studying the undergraduates' conversations through the function–behavior–structure method [10], research shows that if content-based analysis is not the focus of study, there is no significant difference between the more laborious function–behavior–structure and using more informal methods, such as a turn-taking approach [10]. A simpler approach indicates involvement of team members and may be analyzed by a single coder (first author), which was a constraint of this study. Moreover, meeting and dialogue data among team members were not collected. Thus, the authors relied on interview and perceptions of team members regarding the project narrative. Perceptions of the undergraduates toward their teamwork process constructed the knowledge gleaned by this study. The authors purposefully used this framework to facilitate success by following others' recommendations [7]. The authors functioned in a detached role, while the participants were the main knowledge builders. Although present at weekly meetings and interacting with all team members, the authors strove to bracket themselves from each project, minimally participating in meetings to concentrate on taking observational field notes.

The three projects are described in Table 1 including a description of team members included in this study, their declared major area of study, a brief description of their project, and a description of how STEM disciplines were integrated in the execution of each project. Because the project questions were defined by the undergraduates in terms of scope, full integration of all disciplines of STEM, although encouraged, did not always happen. For example, mathematics was used as a tool more so than a concept. Others have found that college student teams used mathematics as a tool and underutilized mathematics, thereby not fully integrating STEM [32]. The authors followed [32] recommendations, including (a) purposefully selecting teams to encourage partnerships, (b) encouraging teams to utilize online resources, (c) emphasize the application of the project to real life, and (d) encourage undergraduates to reflect on their own experiences when planning lessons to deliver to a younger audience.

The undergraduate teams were purposefully selected by the authors to maximize integration of STEM. The undergraduates applied to be a part of the project and all participants consented to take part in this study. IRB approval was given by the supporting university (blinded for review). Undergraduates were sophomores or juniors at the beginning of the program; people from traditionally underrepresented groups were encouraged to apply, although data pertaining to those characteristics were not collected as part of this study. Nine undergraduates were accepted into the 2020 cohort, forming three teams of three undergraduates each. The GPS and Cell Signal teams were composed of one engineering major, one science major, and one education major. However, the Microbes team was slightly different with two engineering majors and one participant double majoring in science and education. That double-major participant left the project early due to issues related to the COVID-19 pandemic. A replacement was found who held a prior degree in science while pursuing a certificate in secondary education. Although the changes in participants of the Microbes team caused a departure from the authors' plan of similar teams of undergraduates, a collaborative, engaging, skill-based, and real-world problem set was still the foundation of the Microbe team.

Results are based on data collected during interviews with each participant and observational field notes during weekly meetings and teaching in the pre-collegiate classrooms. The authors conducted one-on-one interviews with all team members in a semi-structured manner. Due to the COVID-19 pandemic, the authors conducted some interviews in person, while others were conducted over web conferencing software Zoom. Interviews were recorded and transcribed verbatim. For the analysis of the team partnership levels, the continuum presented by Mullinix [45] was utilized and bolstered by the previous work by Burrows [47]. Basically, there are three stages of the partnership where the least developed is the pre-partnership, followed by the partnership (little p), and the most developed is the Partnership (big P). The dimensions of these three stages are focus of interaction, activities/projects, time/orientation, benefit, trust/respect organizational structure, organizational strategies, influence, and contracts. Each team was holistically assessed according to this continuum.

3. Results

The lesson plans were a product indicating effective and efficient planning of lessons and activities that engaged a pre-collegiate class and provided motivation to learn STEM. The process of developing partnerships and teamwork skills contributed to the quality of the products and is described within each team in the following sections.

3.1. Microbes Team

The Microbes team is described in Table 2. This team differed from the other two teams in two ways. First, it was composed of an education major who holds a prior degree in geology, and who joined the team halfway through 2020 as a replacement for a team member who left the project due to issues related to the COVID-19 pandemic. In addition, the Microbes team was composed of two engineering majors, civil and mechanical, instead of one engineer and one science major.

Table 2. Microbes team summary, successes, challenges.

Team Member and Major	Summary of Learning Learned from or by . . .	Successes	Challenges
Meg: Mechanical Engineer	Others Teamwork Teaching Independent research	Integrated relationship of integrated STEM and teamwork	Impact of loss of team member
Mike: Civil Engineer	Doing Others (remotely) Teaching	Teamwork was separate but coordinated	Impact of loss of team member Teamwork was remote
May: Geology, Secondary Science Education	Others Independent research “The Engineers”	Teamwork was a relationship	Felt separate, “them and me” Joined team late Longed for more involvement

3.1.1. Integrated STEM—Microbes Team

The Microbes team perceived a level of benefit from the project, both by learning from each other and by learning content outside their major area of study. As Mike summarized, “I went from knowing nothing about Arduino besides the fact it was a microcomputer brain to actually being able to code and attach parts to it.” Mike gleaned this knowledge by learning from others online in chat rooms and discussion boards, where he modified examples posted by others.

Mike considered his work with the other engineer, Meg, to have been productive and cooperative. He described:

> We were pretty in sequence. [Meg] obviously took charge of more the actual, like, physical design and layout, where I took control over, like, the electronics and the motors and stuff like that. But we still had to work very closely together, and it was very integrated, what we did. Or, like, the stuff was very reliant on each other. We had to test them with both parts.

Meg realized a missed opportunity to expand her locus of influence but also recognized the value of experiencing an engineering design process firsthand. She summarized the project:

> Well, I’ve realized, and this is something you would never learn in an engineering classroom, that you can have all these ideas, and they could be a really good idea, look super pretty on paper, but they’re not actually practical. And I went through so many different designs, and I was like, oh this is awesome! And then I’d show it to [Mike] and he’d be like, yeah, but that and that and that . . . and I’d be like, yeah, that’s a really good point. Gotta change it. So, I don’t know, I think my understanding of the engineering process overall definitely improved. Um, like,

> I think there was an opportunity for me to gain a better understanding of, like, the electronic components, except I didn't really take [Mike] up on that. But it was a potential.

Meg learned from the education major as well. Meg said that May "widened my range of thought" by presenting a different, science-focused perspective on the project, where "sometimes I kind of felt like a student too." Meg's role in the classroom as guide helped her learn the content:

> It helps me understand the project more when I'm trying to explain it to other people . . . I think it helped me realize, like, the good parts and the bad parts of the payload, like the parts I wasn't really able to explain? Those were the parts that I should reevaluate.

Meg learned confidence from observing May teach in the K-12 classroom, explaining that, "after watching her in the classroom, I feel like I could possibly do that if I had to."

The Microbes team faced a challenge by losing a team member due to impacts of the COVID-19 pandemic. Thus, the team was left with two engineers. An education major, May, joined the team in fall 2020, more than halfway through the project and after the project was chosen, payload built, and a test launch performed. May joined the team mere weeks before the team went into the classroom to teach lessons and activities and encourage pre-collegiate students to participate in the launch. The close timing and late start affected the integration of the scientific and engineering content with education and tailoring the payload-related concepts to a pre-collegiate audience as May scrambled to design lesson plans and activities that pertained to the project and research the concepts to provide a foundational context to the lessons. Although she found meeting helpful and enjoyed getting to know the two engineer team members, May said, "sometimes it did feel like I was separate from the engineers . . . . I had to do a lot of research" in order to understand the Microbes content, "I had to really dig in." Although May gave credit to the engineers' role in the classroom, "they were great when they were explaining, the, you know, engineering portion", she wishes she would have had an "explicit part for them, to be more involved in" the classroom portion. She suggested that "having a more structured plan and structured meetings between me and [Mike] and [Meg] um, would have helped their involvement in the classroom."

3.1.2. Partnerships and Teamwork

May acknowledged the challenge of joining a team midway through the project, saying "coming in earlier probably would have helped a lot, just with my communication with them, and you know, us getting comfortable with each other and figuring out what each other's expectations were." She said, "it would have been nice to know them for longer" which indicates a perception that she did not fully move from getting to know them into true collaborative teamwork. This feeling of incompleteness was sensed by May, who "would have loved to be more involved in, like, the payload development. Because even though I'm not an engineer, you know, I have a STEM background . . . I think it would have been wonderful to be there for the whole year".

Mike described the impact of the unexpected team member change on the teamwork process:

> We kind of put the [lesson plans] on the education major at the last minute. And uh, because they kind of had to show up and then take charge of all that. While me and [Meg] were working on the actual payload from uh, since back in January, so that was a little separated, but that was just kind of because of the events that unfolded this semester, or this year.

Mike acknowledged the consequences of having "to get an education major at the last minute instead of having them from the start, who actually worked with the package and would have seen how far we've progressed." Meg as well felt the impacts of the constraints dictated by the COVID-19 pandemic. She described the impact:

> Just like because of COVID, and it being kind of like scared to be together for the first part of the spring, and in the summer. It was hard to work together, me and [Mike], I think. In normal times, I think we would have done a lot better, having a good solid team foundation.

Meg felt that as the pandemic progressed, teamwork broke down. She explained:

> I think at the beginning in the spring, when it was [former team member, Mike] and I, I think there was a lot more integration. We would have weekly Zoom meetings or whatever where we would just discuss where we were all at. Maybe give each other ideas of what to look for, what to do. But then, I can't really say what happened, but then there was just this time that we were all kind of separated and kind of just working on our own stuff. We would come to the weekly meetings, or on Zoom, during the summer. But I don't know, there wasn't a whole lot of integration . . . and I don't know if it would have been different if we were more in-person, if COVID wasn't a thing.

The changeup in team members may have impacted how the team integrated the content with the lessons and how integrated STEM content and developing a partnership were impacted by not knowing each other for very long. As May described:

> I feel like the [roles] were pretty separate. Like, they pretty much did the engineering, they figured out all that. Of course, they did all that before I even joined the project so there wasn't really a place for me within that. Um, and I felt like, you know, my teaching aspect was completely separate from what they were doing. Other than, you know, I have to integrate the payload and the balloon launch into the lessons.

However, May still perceived that "they taught me a lot about the payload" and that "they were really helpful to consult in the engineering portion of this".

3.2. GPS Team

The GPS team is described in Table 3. This team is one of the traditional teams. Each member was an undergraduate, sophomore or junior in credits at the beginning of the project. The GPS team was composed of one engineering major, one science major, and one education major, who was pursuing a double major in physics as well as secondary education.

Table 3. GPS team summary, successes, challenges.

Team Member and Major	Summary of Learning Learned from or by . . .	Successes	Challenges
Glen: Computer Engineering	Experts Independent research	Taught teammates	Integration and teamwork "difficult" Disciplines remained separate
Gail: Physics	Experts Doing Teammates	Learned skills outside major, e.g., soldering, building payload, software	COVID restrictions kept team from in-person classroom experience
Gabe: Physics and Secondary Education	Experts Hands-on activities Profs and online community	Jigsaw—did not know all the pieces, but understood enough Developed a team	Team "rarely worked together" but "on the same page" Team roles defined and separate

3.2.1. Integrated STEM

Members of the GPS team described learning outside of one's discipline as a perceived benefit. Gabe, the physics education major, said:

> Well, I didn't have much of an understanding at all before the idea was presented. I had never heard of radio occultation. I had never known too much about GPS either. Um, so definitely my understanding developed as we did more research.

Gabe spent the summer building an antenna for the payload, which was outside his area of expertise and experience, and ultimately discarded in favor of a pre-built antenna. However, he considered it a worthwhile challenge and grasped the design constraints while researching how to build or acquire the item. As he described a little patch antenna that got the job done. But I did all sorts of research this summer learning about that. Um, how those work, and I built a few prototypes, and tried to find one that would get the job done right. There, you have to think about the directionality of it. Um, and the wavelength that you're trying to pick up. And there's a range of wavelengths that we were trying to pick up, and we wanted a satellite that goes to all directions because we weren't controlling the orientation of the balloon. Um, so that was a good challenge to find an antenna that did that.

The education major respected how STEM majors conducted research. Gabe mentioned:

> I was definitely impressed with the way my team did research. I just couldn't think of a single idea . . . and they really left the chart with that. And that was impressive to me. Um, how they had an idea, without having a real teacher or curriculum or anything, just like grab on to an idea and then learn a bunch about it.

This respect developed into a frame of mind that the authors liken to jigsaw-style active learning, in which individuals learn a part of the whole, then communicate to combine their knowledge to socially construct the whole. As Gabe explained, "I can say I still don't understand completely like the computation behind it, um, but I think I have a better understanding of what the components are, now." The engineer member of the team took on responsibility for the computation side of the payload project.

Glen, the computer engineering major, described the project as "where I've learned the most, ever. I learned a lot in this project." Glen described his experience, "I was surprised at how difficult it would be, I'll be honest, and how complex." In terms of content, Glen researched how GPS and satellites work. In terms of engineering design process, Glen mentioned learning how to collect data, data communication, and data processing, or analysis. Glen also mentioned learning a new coding language to analyze the data. Finally, Glen mentioned learning how to use tools such as atmospheric sensors and a thermocouple, which he had never encountered prior to this project. He conducted research both on Google Scholar and product sheets, as well as user guides and what he described as "self-learning", or trial-and-error. Glen was confident that the knowledge and skills he learned from this project would be helpful in his future senior capstone design class.

Gail, the physics major, also learned from others, including an informal interview with a leading scientist in the field, and more hands-on activities such as soldering parts of the payload together. She demonstrated awareness of gaining a locus of influence from others. Gail said, "I learned a lot from my teammates. I think they are both very, like, brilliant and driven individuals . . . they taught me things all the time . . . I'd say we all learned from each other a great deal".

3.2.2. Partnerships and Teamwork

Glen said the project "gives you the opportunity to learn about stuff, so it gives you a lot of experience. Both technical and, like, soft skills too, when you're trying to teach and then, um, working in a group." Glen, the engineer, learned from the education major. He described, "I did learn a lot about teaching from [Gabe], seeing how he kind of did things, it kind of gave me ideas of how to teach things when it was my turn to, like, talk about how radio occultation worked and stuff".

Although the GPS team worked as a partnership, team members often worked independently in discipline-specific roles. As Gabe described the roles, "I think they were pretty separate. Um, we all collaborated on the side of who was going to do what. But we rarely actually worked together." As Gabe explained:

> But I think we were on the same page for most of it. I don't think that's bad, like I think that we all knew what was happening and no one was getting left out. But we just had our separate jobs to do.

On the other hand, Gail perceived strong teamwork and partnership development. She described the project as a "collaborative effort overall" and that "we all collaborated um, and on lesson plans too" but that the team "didn't have assigned roles." She gave credit to teammates for teaching her how to solder, build parts of the payload, and learn about software. "I feel very fortunate to have had teammates like them. Because, yeah, they were always, like, if I didn't understand something, they would explain it to me." This team in fact did deliver lessons together, albeit remote synchronous with the partnering pre-collegiate school due to distancing requirements, and recorded videos of experiments, demonstrations, and mini lectures together that they shared with the partnering school.

3.3. Cell Signal Team

The third group, the Cell Signal team, is described in Table 4. This team was the other traditional team. As with the GPS team, all members were undergraduates in their sophomore or junior year at the beginning of the project and remained with the project to completion. The Cell Signal team was composed of one engineering major, one science major, and one secondary education major, who intended to teach English.

Table 4. Cell Signal team summary, successes, challenges.

Team Member and Major	Summary of Learning Learned from or by . . .	Successes	Challenges
Carol: Mechanical Engineer	Others Teaching Independent research	Teamwork is crucial Took steps to improve	Communication a "struggle"
Cal: Physics	Doing Experts Teaching	Perceived content as interdisciplinary, complex	Would have liked more collaboration Teamwork difficult because "online"
Carla: English Secondary Education	Others Independent research Experts Communicating	Took leadership role in K-12 class, earned respect from teammates. In turn, recognized others' expertise, appreciated explanations	Felt separate, "them and me" "Didn't question" separate discipline dynamic

3.3.1. Integrated STEM

The Cell Signal team learned from others while staying within the confines of major of study. The team members held a high level of trust and respect for each other's expertise and readily admitted learning from each other. Carla said the STEM majors "did a great job making sure we had all of the parts that we needed to get the data" and that "I did learn some things about the payload . . . the circuitry they used, the antennas they used . . . different receptors and receivers" that she translated, with the STEM majors' assistance, to visualizations "that were good for the lesson." Carla appreciated the work the STEM majors put into the classroom visit, saying they:

> Did a good job of explaining, like, how the pieces of our payload operated. And, like, what the technology was. And we talked about circuitry and all of those things. And so, we really did bring in a lot of those technological engineering pieces.

Cal, as a physics major, described a growing respect for "the difficulty of teaching difficult concepts to children." Carol echoed this sentiment, saying she learned "how much you need to know to be able to teach someone else". She mentioned a respect for Carla's skills in "controlling a classroom" and "maintaining their focus" portions of her "teaching style".

Carol, the mechanical engineer, showed respect for Cal's knowledge, crediting him for finding documentation about their experiment "that said that we were actually operating outside of its range, and so that would account for most of the spikes that we saw." Carla, the education major, learned from independent research, "for me, it was learning it. I had to learn the material, and then figure out, okay, how am I going to teach this to an audience?" as well as learning from experts, "Pretty much all I could do was talk to people." Carla also learned from the STEM majors, complimenting then on "a good job of telling me what sort of things we were working on, and what the exact focus and what the exact capabilities of our payload were. So that I could plan around that." Carol agreed, saying:

> [Carla] did a really good job of coming in and understanding and asking the right questions to make sure she understood, and then the activities that she was able to put together I thought were really good as far as, like, helping the kids to learn about it as well.

Carol, the mechanical engineering major, described finding a better understanding of how the engineering process works . . . a lot of mistakes made along the way . . . that is where I learned the most . . . learning about the details of the process . . . like how our specific board works . . . operating outside of the board's range...just understanding that experiments don't yield ideal results.

Carla, the education major, regretted the missed opportunity to engage the pre-collegiate students in hands-on learning:

> I would have liked to go a little bit more in depth on, like, how our payload worked. I think that would have been interesting for students to actually get to look at our boards and at our antennas and learn about how all of these different pieces come together.

However, Carla valued her role as delivering the content in ways that pre-collegiate students could understand and engage with, to "translate what [Carol and Cal] are saying about these concepts and about our payload and about the project and give it to students in a way that they could understand. I would say that I was the translator." Cal, the physics major, supported that, explaining that in the classroom, "in order to um, to distill it down into a simpler version, I had to have a better understanding of the foundations of those ideas." Cal mentioned, "those concepts are very interdisciplinary, and more complex than we were able to teach them".

3.3.2. Partnerships

The Cell Signal team did not develop into a fully integrated partnership. Carla's perspective was:

> I wish that we would have incorporated with each other or worked with each other more. Um, because it felt sometimes that like [Carol] and [Cal] were their own separate team and then it was me. And I was just trying to grab at all the ideas that they were getting, um, I'm surprised we weren't more of a unit.

Although Carla identified the lack of teamwork as discipline specific, saying, "[Carol and Cal] didn't question things that I did in the classroom I didn't question things they were doing with the payload. Um, and that's just kind of the dynamic that it was, which is fine" she also hinted at a communication issue, "no matter how much we talked, we could never quite get there" and "I think from the outside, it looked like it came together, but from the inside, it didn't feel like it came together."

Cal seemed to support that perception, saying that "we only, I guess, interacted to help [Carla] understand the technical side of the project." Cal regretted that there was "little collaboration" saying, "I would have liked to, um, to collaborate more." Cal was frustrated by spending the summer doing "an entire separate project that didn't work" and had mixed feelings about switching to Carol's choice of project, something he said Carol "kind of did this as an offshoot" and "then we hopped on to her idea." Cal said that he wasn't sure if

Carol "didn't trust my abilities, or if she had, like, the foresight or if it was just because we were so disjointed, we were doing our own things" but his initial idea to do a project focused on radio signals morphed into a project studying cell phone signals. Carol, on the other hand, did not perceive this frustration, saying that "I think once we decided on [cell], I think that, um, it went as smoothly as we could have asked for." However, Carol spoke about a "struggle" with communication, which she said eased "once we started seeing each other in person more." Cal supported this perception, mentioning that he had poor "online" skills. Carol suggested that she took on a leadership role in the team, "I made it a goal to kind of, like, just say, like, hey, let's meet at this time and this place, and we definitely started doing that more. And that was helpful, um, for sure it was helpful for me".

3.4. Cross-Case Analysis

The authors analyzed how the three teams functioned holistically and developed partnerships. The partnership model that the authors used was a modified version (Table 5) of the Mullinix model [20], and the authors modified it to pertain to undergraduates working together toward a clearly defined goal. A few categories were eliminated from the original scale because those areas did not pertain to the needs of this study. The modified partnership development continuum is provided in Table 5. The authors describe how the three teams functioned in each dimension and include rationale for modifications to the model. The levels the teams reached in each dimension are indicated by lightly shading the boxes in gray.

Table 5. Modified model after Mullinix (2001).

Dimension	Pre-Partnership	Partnership	Partnership
Focus of Interaction	Getting to know each other	Working to achieve mutually valued objectives (payload and lessons)	Developing and implementing payload and lessons together
Activities/Projects/Programs (Payload and Lessons)	Limited—specifically defined relationships which allow teams to become acquainted with each other	Opportunistic—teams work together because it is convenient and appropriate (a good match)	Integral—teams develop joint payload and lessons that grow directly out of common skills and interests
Time and Orientation	N/A	N/A	N/A
Benefit	Increased Networking—teams develop relationships and skills	Increased capacity—teams able to do more and/or access more resources than they could alone	Increased status—teams able to become more than what they would be alone
Trust and Respect	Building trust and earning respect	Trust and respect exist among some team members	Mutual trust and respect throughout team
Team Structures, strategies, and information access	Completely autonomous and separate	Separate but coordinated	Appropriately integrated and developed together
Locus of Influence	Separate	Shared or differentiated according to expertise and capacity	Integrated with acknowledgement of expertise and capacity
Written Agreements or Contracts	N/A	N/A	N/A

Note: Gray boxes show the levels accomplished by all teams.

The first dimension, **focus of interaction**, was of prime importance to the authors. The authors guided the teams to progress beyond getting to know one another to fully collaborate and integrate their skills to develop and implement the payload. However, the line was fine between working on the payload and working together on the payload. Observations collected during weekly meetings documented team meetings held outside the official weekly meetings, but the authors, who acted in dual roles as researchers and supervisors, did not attend these meetings. Further complicating the issue for the 2020 cohort was the onset of the COVID-19 pandemic and associated requirements of remote communication. Team members coped with the rapid transformation to a situation mandating remote learning, social distancing, mask wearing, and quarantine for all but the first third of the project. Each team, though, made efforts to progress into the partnership stage. This process occurred by informal meetings, social get-togethers, and synchronous Zoom meetings before or after the official weekly meeting. The Microbes team was able to progress through the pre-partnership stage considering the change in team members. The GPS and Cell Signal team unanimously perceived they progressed into the partnership (little p) stage, with some members perceiving teamwork reaching Partnership (big P) stage. The authors' conclusion is that all three teams landed squarely in **partnership**, with occasional leaps into Partnership for this dimension. The members all worked to achieve their goal of successful payload launch and lesson plan, but they did not work seamlessly together all the time.

The second dimension, which were the **products** created including payload and lesson plans, were also of major importance to the authors. Here is where the authors noted a specificity of roles taken on according to one's major area of study. For example, engineers did not typically take part in lesson planning. Nor did the education majors become deeply involved with building the payload. However, there were some overlaps. For the GPS team, that may be due to the education major also double majoring in physics. He spent the summer building an antenna, in this case a direct piece of the payload. Although the antenna was ultimately not used, he shared that he learned "a lot" from the experience. This dimension fit into **Partnership**, in that team members contributed equally to the success of the project.

A perception of **benefit** from the project was felt by all the team members, and all mentioned they had learned from each other. Learning from each other helped transcend disciplines and truly integrate the STEM aspects of the payload as well as the educational aspects of lesson planning and teaching. Each team increased status and were able to become more than what they would be alone. Each member contributed something to the project; no one team member took on every task. Together, the team delivered lessons and activities to a pre-collegiate classroom that would have been impossible for a single person, STEM major or education major, to accomplish alone. Here too the teams clearly achieved a **Partnership**, achieving and becoming more as a team than they would have alone.

The **trust and respect** dimension varied among the teams. The Microbes team suffered from a loss of a team member due to difficulties brought on by the pandemic. That team, understandably, had less history with the replacement team member, although all members indicated a level of respect for one another's expertise, and a regret that the time was insufficient to get to know one another well. The GPS team valued and respected each other and could name specific instances where they were impressed. The Cell Signal team, although hampered by the challenge of changing project topics, harbored a feeling of respect as well. Because the authors heard mentions of "struggles", "frustrations", and "didn't come together from the inside"; however, they hesitate to assign this dimension higher than **partnership** level. Although some team members trusted and respected others, and many disclosed so during the final interview, listening to what was unsaid indicates there may have been some difficulties here and there with team members.

The **locus of influence** was marked among the undergraduates. Every STEM major mentioned respect and admiration for the education major's demeanor and management skills in the classroom. Even STEM majors who did not include education majors while building the payload readily followed the expertise of the education major when it came to lesson plans, classroom management, and so forth. STEM majors concentrated on "simplifying" content during the classroom visits and viewed themselves as something akin to subject matter experts, focusing exclusively on content. They recognized the difficulty in keeping pre-collegiate students focused and engaged and indicated respect for how the education major handled this issue. The STEM majors did not indicate any issues regarding each other's expertise, but nor were they overly appreciative. The authors would place this dimension into a **partnership**, due to the division, often mentioned, between STEM majors and the education major. The "them and me" mentality suggests a partnership, in which the project was shared or differentiated according to expertise (major area of study) or capacity. The authors made efforts to nudge this into Partnership and full integration by asking the entire team design and deliver lessons to the pre-collegiate audience but left it up to the team to determine how the lessons would be organized, which generally fell to the education major to delegate.

The **team structures**, **strategies**, and **access to information** were combined into one dimension. The three teams aligned in these areas. In the Cell Signal team, the education major worked separate from the STEM majors. The education major developed the lesson plans mostly in isolation, although seemed to be willing to ask for help when needed. The Microbes team also had the STEM majors working in isolation as well due to the unexpected departure of the education major and the replacement not coming in until fall. The GPS team worked together most often of the teams. Besides the education major working on a piece of the payload most of the summer, the STEM majors came together to record video to share with the pre-collegiate students and participated in the experiments and demonstrations shared via remote synchronous with the pre-collegiate classroom. One reason why the authors decided to combine these categories is the COVID-19 pandemic. The teams began working in early 2020 under normal circumstances, and then needed to abruptly shift in March. The isolation, remoteness, and quarantining were more unfamiliar and stringent during 2020, and it is unknown what effect this had on teams' working preferences (separately or together). Therefore, the authors give these dimensions less emphasis and place each team into a **partnership** level, separate but coordinated.

Time and orientation, along with **written agreements and contracts**, were not considered during this study because of the nature of those dimensions. All the undergraduates were under the same time constraint, one calendar year, thus nullifying any differences. The 2020 cohort began brainstorming and developing the payload the spring semester, work was optional during summer, and concluded with teaching lessons and collecting the data from the payload fall semester. Although time on task undoubtedly varied among the teams, no documentation exists for the informal and social meetings outside of what was mentioned during the exit interviews. Likewise, all undergraduates signed an agreement for compensation and expectations for time on task were delivered verbally by the supervisors.

4. Discussion

To summarize, teams reached the highest **Partnership** level with:

- Activities/projects/programs (products created, both lesson plans and payload);
- Benefit each team member perceived.

Teams achieved a moderate **partnership** level with:

- Focus of interaction;
- Trust and respect;
- Locus of influence;
- Team structures, strategies, and access to information.

The authors did not consider two dimensions for this study:

- Time and orientation;
- Written agreements and contracts.

The authors found a relationship between the degree of STEM integration and the strength of the partnerships formed. In general, the authors found, qualitatively, that STEM integration and partnerships seemed to increase together. The products of payload and lesson plans were supported by team members working together to become more than what they would have alone. Moreover, all teams progressed into partnership (little p) from pre-partnership, and establishing this foundation allowed teams to accomplish the higher levels in benefit and products. Engineers felt confident about teaching concepts to others after watching future educators' demeanor in a pre-collegiate classroom; educators felt confident delivering complex material to a younger audience when STEM majors were present to address questions and confusion. The level of STEM integration increased with trust and respect among team members. The more team members trusted each other, the more they learned from each other during this project. Some team members viewed the project like a jigsaw exercise, a term used in the education discipline, in which not everyone needed to learn everything about the project, but everyone contributed according to their expertise. Hands-on learning led to integration and appreciation of the locus of influence. For example, a physics major learned to solder from a fellow team member, something she had never done before and contributed to her skill set. The authentic nature of the project as opposed to pursuing a theoretical question encouraged integration of STEM integration and meaningful learning. As Gail explained, "when you think about how GPS radio occultation works, like in theory in your mind, it's definitely different when you're actually seeing, um, readings from when, like, when we took it from that high hill . . . "

The teams overall progressed from pre-partnership into partnership and then Partnership levels, which is encouraging given the constraints imposed by COVID-19 pandemic social distancing. Even the Microbes team, who faced the challenge of a new team member, made strides into partnership levels and establishing trust and respect. Each team seemed firm in their resolve to see the project through and adapted to various constraints. The weekly official meetings with the authors were a mixture of in-person and remote synchronous, dictated by quarantine and isolation requirements. Access to pre-collegiate schools varied as well. The Cell Signal team enjoyed full access with no restrictions at the private elementary/middle school they visited; the Microbes team were granted visitor access but were required to mask and social distance at the high school for at-risk students they worked with; and the GPS team were not granted access to the middle school in another town and had to deliver all lessons remotely using synchronous software and web cameras.

The nature of the challenges presented by the COVID-19 pandemic makes assessment of STEM integration and partnership skills overall an uncertain venture and represents a limitation to this study. Nevertheless, nuances of how each team navigated integration of STEM and teamwork skills would have presented whether the pandemic had happened or not. Those nuances represent facets of each member's personality and brought dynamics to how the team functioned. The pandemic threw a confounding factor into this study but did not derail the team's collective will to produce or the conclusions drawn by the authors.

5. Conclusions

Overall, this study showcases the importance of partnerships and teamwork to integrated STEM and indirectly the importance of authentic and hands-on activities to integrated STEM. The authors found there is a relationship between quality of formed partnerships and the quality of team products. Team members progressed through the pre-partnership stage to reach partnership (little p), and in some cases Partnership (big P) status and achieved their common goals. Undergraduate teams progressed from pre-partnership to partnership in all other areas studied, which indicates that fulfilling the pre-partnership prerequisites was necessary to achieve the higher Partnership levels in the dimensions of benefits and products. Collaborative learning helped teams accomplish higher levels of partnership, underscoring the value in this learning approach other researchers have described [41,47]. Moreover, team members often stated in their interview the importance of communication and how the lack thereof increased their uncertainty about the project [8,16,47].

In multidisciplinary teams, gaining the perception of benefit from each member of the team is essential to producing a product of quality. Team members used problem-based learning to rely on each other's area of expertise (indicated by their chosen major area of study) and learn from each other, which supports researchers' claim of benefit to using a collaborative and problem-based learning approach [7,32,36]. Moreover, teams integrated the disciplines of STEM to build a payload that relied on aspects of each STEM discipline. This integration of discipline knowledge was crucial for a successful problem resolution and indicates that STEM integration can solve some of the issues discussed by researchers [18,40].

What should you do to build partnerships? The authors recommend that those looking to assist in partnership creation pay attention to the following dimensions adapted from [45]:

1. Focus of Interactions—Teams develop and implement activities together to assist in team building, unified objectives, and end targets;
2. Activities/Projects/Programs—Teams develop integral activities/projects/programs that grow directly out of common skills and interests to create cohesion;
3. Time and Orientation—Teams work on open ended and goal-oriented problems and can explain short- and long-term objectives and the overall mission;
4. Benefit—Teams (not just an individual) are able to become more than what they would be alone and should be able to articulate this accomplishment;
5. Trust and Respect—Teams build mutual trust and respect with all members through expectations and norms;
6. Organizational Structure—Teams work together, not as separate individuals, but instead as coordinated and transparent interactions with all members;
7. Organizational Strategies and Information Access—Teams develop activities/projects/programs together and sensitive information is promoted together;
8. Locus of Influence—Teams share the responsibility, based on expertise, to create tasks and actions for the whole team assisting with whole team ownership;
9. Written Agreements—Teams write out areas of interest, expectations, and commitments to each other and review them periodically for continued growth;
10. Conflict Management—Teams watch for conflicts and follow expectations and norms in discussing feelings, actions needed, or soliciting outside intervention.

Future research might focus on partnership integration versus jigsaw regarding STEM integration in authentic, ill-defined projects. Are there tradeoffs? Might one be preferable to the other? Are they different or two sides of the same coin?

Overall, this study assisted participants with providing hands-on, authentic activities, built on the necessity of communication skills and teamwork, which are 21st-century skills [1,2]. The soft skills, like communication, were shown to be important in creating stronger partnerships, along with the other dimensions outlined. This study might provide a means to facilitate undergraduates to practice both hard and soft skills in building partnerships as they engage in both teamwork and creating authentic, meaningful products.

Author Contributions: Conceptualization, T.J.K. and A.C.B.; methodology, T.J.K.; validation, T.J.K. and A.C.B.; formal analysis, T.J.K. and A.C.B.; investigation, T.J.K.; resources, A.C.B.; data curation, T.K.; writing—original draft preparation, T.J.K.; writing—review and editing, A.C.B.; visualization, T.J.K. and A.C.B.; supervision, T.J.K. and A.C.B.; project administration, T.J.K. and A.C.B.; funding acquisition, T.K. and A.C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by a National Science Foundation LIFT grant [#1821566], EPSCoR K-12 EOD [#1655726], and SWARMS grant [#1339853]. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of University of Wyoming (#20191101TK02576 approved 1 November 2019).

Informed Consent Statement: Informed consent was obtained for all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to IRB restrictions and confidentiality of subjects.

Acknowledgments: The authors wish to thank the following members of the LIFT Project and acknowledge their work: Philip Bergmaier, Shawna McBride, Kate Muir-Welsh, and Kevin Kilty.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. National Academies of Sciences, Engineering, and Medicine. *Graduate STEM Education for the 21st Century*; The National Academies Press: Washington, DC, USA, 2018. [CrossRef]
2. National Research Council. *A Framework of K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, USA, 2014.
3. Van Laar, E.; Van Deursen, A.J.; Van Dijk, J.A.; De Haan, J. The relation between 21st-Century skills and digital skills: A systematic literature review. *Comput. Hum. Behav.* **2017**, *72*, 577–588. [CrossRef]
4. Balcar, J. Is it better to invest in hard or soft skills? *Econ. Labour Relat. Rev.* **2016**, *27*, 453–470. [CrossRef]
5. NGSS Lead States. *Next Generation Science Standards: For States, by States*; The National Academies Press: Washington, DC, USA, 2013.
6. Burrows, A.; Lockwood, M.; Borowczak, M.; Janak, E.; Barber, B. Integrated STEM: Focus on informal education and community collaboration through engineering. *Educ. Sci.* **2018**, *8*, 4. [CrossRef]
7. Agogino, A.M.; Shuang, S. Triangulation of indicators of successful student design teams. *Int. J. Eng. Educ.* **2006**, *22*, 617–625.
8. Dong, A. The latent semantic approach to studying design team communication. *Des. Stud.* **2005**, *26*, 445–461. [CrossRef]
9. Giel, L.I.S.; Noordzij, G.; Wijnia, L.; Noordegraaf-Eelens, L.; Denktaş, S. When birds of the same feather fly together: The impact of achievement goal compatibility in collaborative learning. *Educ. Psychol.* **2021**, *41*, 79–98. [CrossRef]
10. Jiang, H.; Gero, J.S. Comparing two approaches to studying communications in team design. In *Design Computing and Cognition '16*; Springer: Cham, Switzerland, 2017; pp. 301–319. [CrossRef]
11. Kristof-Brown, A.L.; Stevens, C.K. Goal congruence in project teams: Does the fit between members' personal mastery and performance goals matter? *J. Appl. Psychol.* **2001**, *86*, 1083–1095. [CrossRef]
12. Locke, E.A.; Latham, G.P. Building a practically useful theory of goal setting and task motivation: A 35-year odyssey. *Am. Psychol.* **2002**, *57*, 705–717. [CrossRef]
13. Louw, L.; Duncan, Q. Teaching industrie 4.0 technologies in a learning factory through problem-based learning: Case study of a semi-automated robotic cell design. *Procedia Manuf.* **2020**, *45*, 265–270. [CrossRef]
14. Marks, M.A.; Mathieu, J.E.; Zaccaro, S.J. A temporally based framework and taxonomy of team processes. *Acad. Manag. Rev.* **2001**, *26*, 356–376. Available online: https://www.jstor.org/stable/259182 (accessed on 16 October 2021). [CrossRef]
15. Mathieu, J.E.; Heffner, T.S.; Goodwin, G.F.; Salas, E.; Cannon-Bowers, J.A. The influence of shared mental models on eam process and performance. *J. Appl. Psychol.* **2000**, *85*, 273–283. [CrossRef] [PubMed]
16. Paletz SB, F.; Chan, J.; Schunn, C.D. Dynamics of micro-conflicts and uncertainty in successful and unsuccessful design teams. *Des. Stud.* **2017**, *50*, 39–69. [CrossRef]
17. Yang, M.C. Consensus and single leader decision-making in teams using structured design methods. *Des. Stud.* **2010**, *31*, 345–363. [CrossRef]
18. Moore, T.J.; Johnston, A.C.; Glancy, A.W. STEM integration: A synthesis of conceptual frameworks and definitions. In *Handbook of Research on STEM Education*; Johnson, C.C., Mohr-Schroeder, M.J., Moore, T.J., English, L.D., Eds.; Routlege: New York, NY, USA, 2020; pp. 3–16.
19. Woods, D.R. PBL: An evaluation of the effectiveness of authentic problem-based learning (aPBL). *J. Chem. Eng. Educ.* **2012**, *46*, 135–144.
20. Merritt, J.; Lee, M.Y.; Rillero, R.; Kinach, B.M. Problem-Based learning in K-8 mathematics and science education: A literature review. *Interdiscip. J Probl. -Based Learn.* **2017**, *11*, 3. [CrossRef]
21. Spuck, T. Putting the "authenticity" in science learning. In *Einstein Fellows: Best Practices in STEM Education*; Spuck, T., Jenkins, L., Dou, R., Eds.; Peter Lang: New York, NY, USA, 2014; pp. 118–156.
22. Newell, C.; Bain, A. *Team-Based Collaboration in Higher Education Learning and Teaching: A Review of the Literature*; Springer: Singapore, 2018; p. 72. [CrossRef]
23. Koro-Ljungberg, M.; Yendol-Hoppey, D.; Smith, J.J.; Hayes, S.B. (E)pistemological awareness, instantiation of methods, and uninformed methodological ambiguity in qualitative research projects. *Educ. Res.* **2009**, *38*, 687–699. [CrossRef]
24. Burrows, A.; Slater, T. A proposed integrated STEM framework for contemporary teacher preparation. *Teach. Educ. Pract.* **2015**, *28*, 318–330.
25. Johns, G.; Mentzer, N. STEM integration through design and inquiry. *Technol. Eng. Teach.* **2016**, *76*, 13–17.
26. Rehmat, A.P.; Hartley, K. Building engineering awareness: Problem-Based learning approach for STEM integration. *Interdiscip. J. Probl.-Based Learn.* **2020**, *14*, n1. [CrossRef]

27. Karaçöp, A. Effects of student teams-achievement divisions cooperative learning with models on students' understanding of electrochemical cells. *Int. Educ. Stud.* **2016**, *9*, 104–120. [CrossRef]
28. Abramczyk, A.; Jurkowski, S. Cooperative learning as an evidence-based teaching strategy: What teachers know, believe, and how they use it. *J. Educ. Teach.* **2020**, *46*, 296–308. [CrossRef]
29. van Leeuwen, A.; Janssen, J. A systematic review of teacher guidance during collaborative learning in primary and secondary education. *Educ. Res. Rev.* **2019**, *27*, 71–89. [CrossRef]
30. Strauß, S.; Rummel, N. Promoting interaction in onine distance education: Designing, implementing, and supporting collaborative learning. *Inf. Learn. Sci.* **2020**, *121*, 251–260. [CrossRef]
31. Robinson, H.A.; Kilgore, W.; Warren, S.J. Care, communication, learner support: Designing meaningful online collaborative learning. *Online Learn.* **2017**, *21*, 29–51. [CrossRef]
32. Ryu, M.; Mentzer, N.; Knoblach, N. Preservice teachers' experiences of STEM integration: Challenges and implications for integrated STEM teacher preparation. *Int. J. Technol. Des. Educ.* **2019**, *29*, 493–512. [CrossRef]
33. Albar, S.B.; Southcott, J.E. Problem and project-based learning through an Investigation lesson: Significant gains in creative thinking behaviour within the Australian Foundation (preparatory) Classroom. *Think. Ski. Creat.* **2021**, *41*, 100853. [CrossRef]
34. Mustofa, R.F.; Hidayah, Y.R. The Effect of Problem-Based Learning on Lateral Thinking Skills. *Int. J. Instr.* **2020**, *13*, 463–474. [CrossRef]
35. Chen, C.H.; Yang, Y.C. Revisiting the effects of project-based learning on students' academic achievement: A meta-analysis investigating moderators. *Educ. Res. Rev.* **2019**, *26*, 71–81. [CrossRef]
36. Ellingsen, P.; Tonholm, T.; Johansen, F.R.; Andersson, G. Learning from problem-based projects in cross-disciplinary student teams. *Educ. Sci.* **2021**, *11*, 259. [CrossRef]
37. Mann, L.; Chang, R.; Chandrasekaran, S.; Coddington, A.; Daniel, S.; Cook, E.; Crossin, E.; Cosson, B.; Turner, J.; Mazzurco, A.; et al. From problem-based learning to practice-based education: A framework for shaping future engineers. *Eur. J. Eng. Educ.* **2021**, *46*, 27–47. [CrossRef]
38. Burghardt, M.D.; Hecht, D. Designing Informal vs. Formal Education Activities—What We've Learned. *Int. J. Des. Learn.* **2020**, *11*, 39–45.
39. Kilty, T.; Burrows, A.C.; Welsh, K.; Kilty, K.; McBride, S.; Bergmaier, P. Transcending disciplines: Engaging college students in interdisciplinary research, integrated STEM, and partnerships. *J. Tech. Sci. Ed.* **2021**, *11*, 146–166. [CrossRef]
40. Siverling, E.A.; Suazo-Flores, E.; Mathis, C.A.; Moore, T.J. Students' use of STEM content in design justifications during engineering design-based STEM integration. *Sch. Sci. Math.* **2019**, *119*, 457–474. [CrossRef]
41. Magen-Nagar, N.; Shonfeld, M. The impact of an online collaborative learning program on students' attitude towards technology. *Interact. Learn. Environ.* **2018**, *26*, 621–637. [CrossRef]
42. Nathan, M.J.; Srisurichan, R.; Walkington, C.; Wofgram, M.; Williams, C.; Alibcli, M.W. Building cohesion across representations: A mechanism for STEM integration. *J. Eng. Educ.* **2013**, *102*, 77–116. [CrossRef]
43. Stake, R.E. *The Art of Case Study Research*; Sage: Thousand Oaks, CA, USA, 1995.
44. Merriam, S.B.; Tisdell, E.J. *Qualitative Research: A Guide to Design and Implementation*, 4th ed.; Jossey-Bass: Hoboken, NJ, USA, 2016.
45. Mullinix, B.B. Nurturing partnership: A Southern African continuum of flexible stages in partnership development. *Curr. Issues Comp. Educ.* **2001**, *3*, 1–12.
46. Couso, D.; Simarro, C. STEM education through the epistemological lens: Unveiling the challenge of STEM transdisciplinarity. In *Handbook* of Research on STEM Education; Johnson, C.C., Mohr-Schroeder, M.J., Moore, T.J., English, L.D., Eds.; Routledge: New York, NY, USA, 2020; pp. 17–28.
47. Burrows, A.C. Secondary Teacher and University Partnerships: Does Being in a Partnership Create Teacher Partners? Doctoral Dissertation, University of Cincinnati, Cincinnati, OH, USA, 2011.

education sciences

MDPI

Review

Pedagogical Models to Implement Effective STEM Research Experience Programs in High School Students

Zubair Ahmad [1,2,*], Mohammad Ammar [1] and Noora J. Al-Thani [1]

[1] Qatar University Young Scientists Center (QUYSC), Qatar University, Doha 2713, Qatar; m.ammar@qu.edu.qa (M.A.); n.al-thani@qu.edu.qa (N.J.A.-T.)
[2] Center for Advanced Materials (CAM), Qatar University, Doha 2713, Qatar
* Correspondence: zubairtarar@qu.edu.qa

Abstract: High school research experience programs (HSREPs) provide opportunities for true science education and expose students to scientific investigations in laboratory settings. Various HSREPs models have been practiced to shape students' research understandings; however, a systematic comparison of the success, challenges, and opportunities of these HSREPs has not been gauged. This article compares the effectiveness of such science, technology, engineering, and mathematics (STEM) based HSREP models reported in the last two decades. We shortlisted seventeen studies on the most effective HSREPs and identified the characteristics of these reports. Results show that student research experiences vary depending on the structure of the model used and the nature of the laboratory setting to which students are exposed. However, there is a dire need to integrate more collaborative and customized research practices to accommodate more students in HSREPs. Additionally, intensive support, mentoring, and coaching are essential to provide students a comprehensive understanding to excel in their research career pathway. Finally, there is a desperate need for further studies to develop the frameworks that can help the smooth transition of high school students into research-oriented university programs.

Keywords: high school; research experience; STEM; scientific inquiry; educational reform

Citation: Ahmad, Z.; Ammar, M.; Al-Thani, N.J. Pedagogical Models to Implement Effective STEM Research Experience Programs in High School Students. *Educ. Sci.* **2021**, *11*, 743. https://doi.org/10.3390/educsci11110743

Academic Editors: Andrea Burrows, Mike Borowczak and Margus Pedaste

Received: 11 October 2021
Accepted: 10 November 2021
Published: 17 November 2021

1. Introduction

Research experience programs (REPs) are leading practices to expose students to scientific research [1]. In principle, REPs provide the students an understanding of the research phenomenon and improve their science knowledge [2]. It builds their research skills and develops critical thinking to analyze, disseminate, and efficiently solve problems. Typically, REPs are being accomplished at the university level; however, there has been a shift in the focus of REPs to the secondary and elementary schools since the last couple of decades [3,4]. High school provides the right time to invite students to join REPs, develop their more profound understanding of subject matters, and integrate their personal and social skills through collaborative and independent research. HSREPs contribute to their intellectual and professional growth and conceptual knowledge and instigate a scientific-thinking mindset. This way, students experience the exploration process of their interests and can be exposed to potential career opportunities in research-oriented fields [5]. Additionally, pre-college research experiences deem to improve the research self-efficacy of students, enhancing their interests' and confidence in conducting research during college [6,7].

When students are introduced to research experience, they understand the inquiry process, problem-solving skills, data collection procedures, and observation processes to draw research findings. The inquiry process reflects the activities, conceptual demands, and values of "authentic science" [8]. The students are indulged in formulating research questions, developing scientific inquiry, and practical understanding of science concepts. However, the REPs are not globally standardized, and studies depict differences across international practices [9,10]. For instance, inquiry-based education incorporates more "hands-on" practices elements and is not frequently "minds-on." The meagerness of established goals in inquiry processes limits the authenticity of a research experience (RE). At the same time, the stress on educating high-stakes standardized tests has diverted the attention away from lab-based investigations. Hence, states have tried to incorporate authentic research practices in secondary education to engage students in effective knowledge-based education [11,12]. In Australia, educators have worked to substitute purposeful contexts in chemistry to create an independent and extended experimentation environment in students. In Germany, pre-experimental activities created opportunities for students to formulate relevant research questions and designs. In the UK, the national curriculum has prioritized the research investigation in school sciences.

Scholars have also recognized that a collaborative environment is necessary to make up an authentic RE to cultivate learning and endurance in science, technology, engineering, and mathematics (STEM) research [13,14]. They have incorporated science epistemology in their program through students, mentors, and researchers' collaboration. Providing students with self-learning mechanisms allows them to focus on collaborative practices in processes of interactions, social support, and task performances [15]. Educators stress the importance of social contexts as a predictor of student learning as well. In particular, the extent to which the research experience is integrated into the school's culture and curriculum may be important. Such an integrated STEM-based program has a notable effect on the quality of the mentor-mentee relationships, an important variable for the learning outcomes associated with authentic research experiences [16]. This mutual engagement encourages recognition in participants involving them in sustained collaborative relationships where ideas, perceptions, and responsibility propagates the research group's functionality.

This study aims to assess the impact of various STEM-based HSREP models on students using a systematic review of the literature. The study covers the chief characteristics, methodologies, and strategies used to implement HSREPs and provide an outlook on the potential benefits as well as the challenges faced to impact the scientific development of secondary education students. We believe that this study will assist other designers and educationists in understanding, planning, and deploying the pedagogical values of STEM-based REs in high school education.

2. Method

2.1. Literature Search

The present study was performed as a systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [17]. We identified bibliographic documents with proposed learning models for HSREPs claiming their effective relation to students' performance through web searches from the online databases of Scopus, ERIC (Education Resources Information Center), and Web of Science. These databases were chosen because of their international recognition, central knowledge in the educational field, and specific content in terms of educational research. In this sense, the resources fulfill the broad coverage criterion and show an optimum database combination. After running trial searchers, the final concluding search was performed in September 2021. Our search query was set up in the following way: (("research experience" OR "research opportunities") AND ("high school" OR "secondary education") AND ("learning model" OR "model" OR "design" OR "type" OR "method" OR "framework")). The search collected all studies where the search query was met in the title, abstract, or keywords of the articles. The search period was not restricted to any time frame. The Scopus and ERIC directory resulted in 184 and 382 hits, respectively, while Web of Science returned 58 hits. In addition, we also used the snowballing method and other external resources like Google Scholar and ResearchGate to identify relevant studies. In total, 634 articles were found.

2.2. Inclusion and Evaluation of Studies

Subsequent screening of studies was required to include only relevant and concise reports. Figure 1 shows the stepwise filtering of the search procedure. The articles qualifying the search strategy were retrieved from the data sources and their abstract and conclusion were carefully examined. To comply with our inclusion criteria, studies had to meet the following: (a) be published in a peer-reviewed journal in the English language; (b) report a structurally devised pedagogical "research oriented" model for high school students; (c) clearly describe the distinguished features of the model; and (d) indicate the effectual aspects of the model features on the students' development. The above-stated conditions were considered for the initial screening of the studies. A provisional candidature of 97 publications was obtained during the initial preliminary screening based on the inclusion criteria. Concerning the exclusion criteria, we scrutinized for the following: (a) absence of a research-oriented methodology of the learning model; (b) review articles and reports with non-quasi experimental procedures; (c) studies with non-traditional and underrepresented student populations; (d) articles focused on other variables like teacher's experience, student disabilities, non-relevant environmental, and other social or cultural factors. Such bibliographies were eliminated.

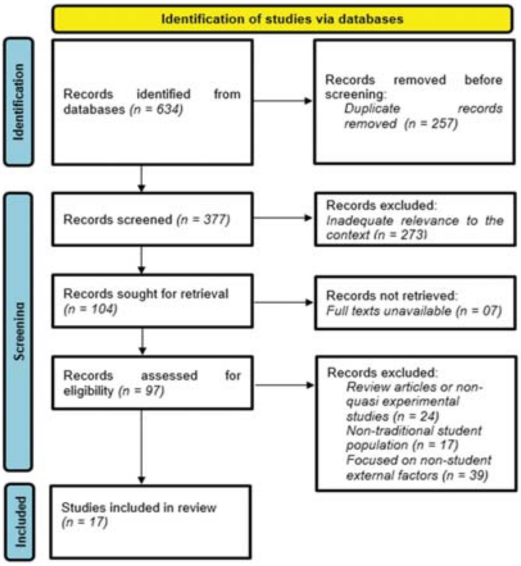


Figure 1. PRISMA flowchart of the search and inclusion process of the literature.

Further, these articles were retrieved from online libraries and precisely studied by extracting their descriptive findings (aim, method, population, results). Finally, the authors performed a concluding selection with careful consideration, which finalized 17 studies for this review. These selected publications met all the inclusion and exclusion criteria (see Figure 1). Table 1 provides the highlights of the eligible studies based on seven notable features: (a) author(s), (b) model design, (c) type of study, (d) population, (e) model effectiveness indicator, (f) outcomes of the study, and (g) country of publication (see Table 1). These articles were analyzed based on the quality of their findings and effectiveness by highlighting the thematic aspects like the specialty of the learning model in their approach, and its correlating outcomes on the efficacy of the student learning process. Thus, this methodological review gives a comprehensive understanding of the various strategies used for high school students to effectively expose them to scientific STEM research.

Table 1. Studies of various learning models for HSREPs, proposed in the research literature.

Authors	Model Design	Type of Study	Population	Model Specialty	Outcomes	Country
1. Lewis et al. [18]	Summer Apprenticeship	Likert-scale assessments	*N* = 7	Career exploration and mentoring	Exposure to a true research environment	USA
2. Sikes and Schwartz-Bloom [19]	Inquiry-based Summer Course	Pre and post-assessments	*N* = 47	5E Model: Engage, Explore, Explain, Elaborate and Evaluate	Gains in knowledge and interest in science	USA
3. Otterstetter et al. [20]	Collaborative laboratory experience	Survey	*N* = 26	An experiential introduction to science	Cooperative learning and career exposure	USA
4. Brooks et al. [21]	Collaborative authentic research	-	-	The partnership between high school students, teachers, and scientists	Understand the nature and process of science	USA
5. Duggan et al. [22]	Summer Research Program	Survey	*N* = 414	Authentic summer research experience increased awareness of STEM careers	Self-efficacy in STEM enhances national STEM capacity	USA
6. Flowers et al. [23]	Introductory field-skills training	Pre and post-assessments	*N* = 121	Scientific exploration and assisting scientists in fieldwork	Scientific enculturation, realistic view of science, and increased confidence	USA
7. Flowers et al. [23]	Advanced field-research internship	Pre and post-assessments	*N* = 51	Extended work experience and scientific communication training	A strong connection between experience and understanding	USA
8. Shoemaker et al. [24]	Mentorship-based research	Pre and post-assessments	*N* = 80	Develop professionalism, career orientation towards STEM	Real-world environment, experience with professionals	USA
9. Gong and Mohlhenrich [25]	Integrated STEM Research	Survey	*N* = 44	Integrate research program into school culture	Understanding the nature of science, part of the scientific community, affinity towards STEM	USA
10. Wang et al. [26]	Research Camp	Survey and interview	*N* = 9	Project-based learning and constructivism theory	Understanding of STEM topics, real-world applications	USA
11. Leuenberger et al. [27]	Field-based experiential learning	Questionnaire	-	Investigate science and experience authentic research	Developed scientific reasoning and experimental technique	USA
12. Oakes et al. [28]	Summer Program	Pre and post-assessments	*N* = 10	Integrate research and education with technological innovation	Knowledge of research and industry, ability to read and use scientific literature	USA
13. Petersen and Chan [29]	Collaborative and Inquiry-based authentic research	Pre and post-assessments	*N* = 54	Collaboration between high school students and community college	Confidence in scientific ability, student engagement, interest in STEM	USA
14. Gong and Mohlhenrich [30]	STEM Research Program	Survey	*N* = 330	Thinking and working like a scientist, gains, and behavior as a researcher	Significant gains in research skills and understanding	China and USA
15. Corson et al. [31]	Virtual Summer Research Experience	Pre and post-assessments	-	Exposure to research, inspiration towards further studies, and networking	Greater appreciation for research, in-depth study, and ethical gains in research conduct	USA
16. Kahn et al. [32]	Summer Enhancement Program	Survey questionnaire	*N* = 25	Strengthen research capabilities and introduce them to future careers	Engagement in research and enhanced knowledge	USA
17. Deemer et al. [15]	Summer Science Program	Survey	*N* = 200	STEM enrichment as authentic research	Increased motivation, retention in STEM, and socialization	USA

3. Results

STEM education is becoming vital to the modern economy and attained much attention from educators and policymakers, in recent years. Increased consideration is being given to impart the pedagogical values of STEM education through research experience programs in secondary education. This is being incorporated through research apprenticeships, summer camps, exposing high school students to university students, and other school-based programs. Such research studies can be classified into two categories: (a) summer research experience models and (b) collaborative and other informal models. This section presents a comprehensive review of these studies and reports on STEM based HSREPs and their key features proposed in the literature. It also discusses the distinct characteristics of both types of models and their correlational effects on student performances.

3.1. Summer Research Experience Models

The summer research experience models are further classified into the following four categories.

3.1.1. Extended Duration SREPs

Gong and Mohlhenrich [30] performed survey on school-based summer research experiences from two countries, the USA and China. Their study reported significant gains on variables that report the positive students' experience and their development through Summer Research Experience Programs (SREPs). These performance indicators included gains in thinking and working like a scientist, personal development, skill development, attitude as a researcher, and aspiration for future career education. Their study also discussed that when high school students indulge in research practices, they should be expected to self-direct their research and perform the stages of inquiry and research individually. Such individual nature of SREPs positively affects their sense of ownership and autonomous nature of carrying out the research process. Another important factor is the duration of the SREPs. Studies have confirmed that the length of the programs considerably affects the learning outcomes in students [25,33,34]. With a long duration of experiences, students can experience authentic research offering multiple iterations of the scientific method, thereby building a diversity of skills in students. However, engaging students in long durations also challenges maintaining their interests and concentration throughout the research program.

3.1.2. Mentorship Focused SREPs

All REs have a common aim to engage the students in hands-on experiences and scientifically develop their skills. Oakes et al. [28] developed a summer research program where graduate fellows mentored high school students. The students and their mentors created a literature review, followed by a research abstract, and finally shared their posters at respective institutions. Such a graduate mentored program helped the secondary students to learn about research resources available on campus, thereby becoming familiar with the campus and the industry. Their pre and post-survey results indicated significant gains in participant confidence in communicating about science and education, understanding the use of scientific literature, and designing experiments.

Similarly, Duggan et al. [22] conducted a summer research program to ensure that high school students with proficiency in STEM get the opportunity to partake in a comprehensive RE. The participating students were aided with mentorship from collaborative teams of faculty, graduate, and undergraduate students. This vertical mentoring process gives adequate guidance and knowledge to the secondary students even after completing the program. Thus, participants gain trust and confidence in STEM fields in addition to their research and scientific abilities. Moreover, such mentorship builds an environment of social engagement in students, which sustains long-term relationships between them and the mentors. This program increased self-efficacy, research interest, and STEM interest in high school students, expanding the established STEM community to enhance the national STEM capacity. Another similar six-week summer model was proposed by Wang et al. [26] to provide high school students a better knowledge of the research process and improve their scientific skills, STEM interests, and equip them to meet the 21st-century skill requirements. Their study reported significant gains in student interests in research and highlighted their motivation to apply the acquired research skills for future learning. Further, [15] established a rigorous STEM enrichment through a SREP among high school students. Results indicated that the program significantly increased the participants' research motivation, competence, retention, and identification with the STEM community.

3.1.3. Inquiry-Driven Real-World SREPs

Sikes and Schwartz-Bloom [19] conducted an inquiry-based science enrichment program to increase the competence of high school students in biology and chemistry, fostering their interests in science careers. Their summer research model followed a 5E (Engage, Explore, Explain, Elaborate, and Evaluate) learning paradigm to provide students with a framework that encourages them to explore controversial topics in detail. This incites a sense of curiosity in students and therefore boosts their interest in learning about the subject. Further, students are guided to extend their knowledge to plan and research an original research question. This enrichment program showed significant gains in high school students' knowledge in biology and chemistry and motivated them to pursue careers in science. Some of the students were even successful in earning honors for their research in regional state fairs. This approach for original research coupled with college-level coursework in high school students enhanced their enthusiasm and success rate in science.

Similarly, Lewis et al. [18] conducted small-group apprenticeships for secondary-level students in biotechnology to provoke student participation in active research projects. Students worked in skilled teams within interdisciplinary fields to present a real-world RE. Their course design provided an opportunity for career exploration and scientific enculturation of the students. The students were able to produce helpful research information equipped with modern techniques by the end of the summer program.

Flowers et al. [23] presented a study examining two consecutive dual-staged career exploration apprenticeship models designed to convey real-world practices and connections to a research career. The initial model offered introductory field-skills training to the 10th and 11th-grade students to engage in scientific exploration at a nature reserve. This way, students were encouraged to step into the environmental research career and clarify their thinking about the scientific research pathway. The students that partook in this program gained a more realistic understanding of the research fieldwork, and, thus, awareness was created amongst the participants about the certain monotonous aspects of the research process. Additionally, students were exposed to professional scientists in mentoring them to apply the basic field skills to actual research leading to a high level of interest in the fieldwork. The graduates of this model were provided with a second consecutive model offering a more advanced field research internship program, competitively selected during their 11th and 12th grades. This time participants were immersed in a research study with university-based research teams and were mentored to perform real research experiments to develop scientific posters. Students were found to have increased confidence levels over time, a deeper understanding of subject matters, and career benefits indicative of a stronger dedication to pursue a research career. This two-stage model reportedly features the characteristic qualities of scientific communities with practices that reproduce themselves successfully. In both models, the students are trained with opportunities to assist professional researchers with one-on-one hands-on experiences. A similar field-based experiential learning model (Leuenberger et al., 2019) was implemented to engross students in a practical inquiry-based scientific process. Simple experiments were developed to demonstrate ecological practices among high school students, providing opportunities to investigate the nature of science and drive integrative scientific approaches like scientific method and inquiry. The students involved gained the ability to develop a hypothesis, scientific reasoning, practical skills, and experiential techniques.

3.1.4. Virtual SREPs

Since the novel coronavirus (COVID-19) outbreak in 2019, the subsequent pandemic posed a distinct challenge for summer research programs. In particular, due to the social distancing and other COVID-19 protocols, research programs directed towards hands-on experiences were not feasible to be held physically. This led many educationists and authorities to devise virtual RE models to continue the smooth functioning of practical apprenticeships and summer internships. One such study was modeled by Corson et al. [31], incorporating research practices in students through digital and online means. Their self-reported student and mentor results suggested a high degree of satisfaction with the virtual program. One unique advantage of such a model was that it offered a chance for meaningful engagement of students who were previously hindered from participating in research due to limited mobility. Similarly, Kahn et al. [32] formulated a supportive environment for online instruction and developed adaptions to the research program with collaborative and holistic approaches, implicating a meaningful RE to students in a remote manner. The physical connections were overcome by building social engagement between students, instructors, and mentors with frequent meetings and decision-making strategies. Such virtual format SREPs can turn out to be effective means of engagement for high school students and seed the development of their scientific identity. Mainly, virtual SREPs hold the potential to lay out new avenues for high schoolers that might have not experienced a full SREP, including students with household and work responsibilities, students in remote and distant places, and students possessing disabilities.

3.2. Collaborative and Other Informal Models

It is well known from the literature, as discussed previously, that authentic REs for high school students have been deemed effective to achieve STEM learning goals, including knowledge of the subject matter, research capabilities, intellectual development, and influence on future career aspirations [8,35]. These developmental effects can be cultivated in high school students through school-based STEM programs, which come in different forms having organizational factors which affect the pedagogical quality of the experience. In other words, the extent to which the research program is integrated into the school curriculum and design is highly crucial for its productivity. This can be executed through collaborations with scientists, universities, and mentors. This partnership provokes a more authentic research environment and helps students to understand the nature of scientific processes. Additionally, simple teacher-led demonstrations of research activities in classrooms and labs have predictable outcomes, thus falling short of the discovery process through iteration practices. Therefore, HSREP models require a structure for students to participate in a complete research process that can achieve unknown outcomes with inquiry-based learning. One such model was formulated by Brooks et al. [21], which involved a collaborative model with scientists to engage students in a large-scale research project. Their study allowed teachers and students to move away from traditional “cookbook” practices and provided the means to expose students to novel practices in research. In the process, students are guided to formulate testable hypotheses individually and make logical connections with their research project. One of the high school students discovered a novel finding that contributed to a research publication. Therefore, students, teachers, and the scientific community can benefit from collaborations like these by opening opportunities for each other and covering up the gaps in their positions.

Another collaborative model was implemented by Otterstetter et al. [20], fostering collaboration between various entities, including faculty members, graduate, undergraduate, and high school students and professionals. They reported that such a diverse network of cooperation increases the effectiveness of mentorship, leadership, and knowledge-based opportunities for all the students. However, successful implementations of such models require careful strategic planning with sound protocols to ensure the smooth administration between the different entities. Similarly, Petersen and Chan [29] suggested a partnership model between a community college professor and high school students along with the school faculty implement authentic practices in students' application of knowledge and experimental designs. The results showed a positive indication with many students motivated to pursue science-based careers and most expressed confidence in their ability to perform scientific practices. Such collaborative models are a cure for various issues educators face in HSREPs, including inadequate funding and lack of laboratory training and resources. Forming collaborative ties with academic institutes, professional scientists and college students can help alleviate some of these barriers. Additionally, institute entities and specialists can work well with school faculty members to adequately design learning approaches that are age-appropriate to the high school students.

For building the STEM careers of students, careful mentorship contributes majorly to develop skills and essential professional practices leading to their bright careers. Shoemaker et al. [24] stressed these criteria and developed a mentorship program that pushes students to take leading roles in performing research with scholars and professionals from collaborating universities or corporations. Their proposed ideology is that students should seek mentors with similar interests from partner institutions to collaborate in their REs. This emphasis on experiential learning opens the opportunity for high school students to develop soft skills like resourcefulness, teamwork, and communication and invokes responsibility to fulfill their desired goals. As a result, a synergistic learning process was formed between mentors and students, with each entity having its shared benefits. At the national level, demonstrations of student talent in various academic and professional corporations highlighted the value of schools' education.

The majority of the learning models reviewed in this study are a few weeks or a couple of months long. One study by Gong and Mohlhenrich [25] reported a two-year, on-campus research project for high school students in the field of their selection. The program's increased duration offered students a vital aspect of the scientific method by performing multiple iterations and in-depth understanding of the process. Moreover, the program demonstrated that STEM integration of an effective research experience also requires other requisitions such as the length of the program, whether participation is required or not, and the number of disciplinary fields in which students can pursue the research. However, one disadvantage that lengthy durations carry is keeping the consistent level of student engagement throughout the program. Moreover, the overall results of such a model were reported to be compatible with the learning goals of STEM REs. Self-report gains of the participants included practical research skills, ability to work like a scientist, incitement to pursue a STEM career, and feeling of being part of the scientific community. The critical takeaway from all these integrated and collaborative models is that establishing and assessing how different HSREPs' design affects student performance and participation needs urgent attention. The diverse range of HSREPs makes it difficult to categorize all the models methodologically. However, the critical dimension remains to understand the degree of integration of the program with the school's module.

4. Discussion

The involvement of high school students in inquiry-driven hands-on experiences provides the critical aspects of their understanding of science. The learning process, particularly when subjected to student ownership, engages students in effective knowledge retention, motivating them towards research [36,37]. SREPs tend to effectively expose these features in their experiences in the models mentioned above, making it one of the most common models implemented in high schools. When students are made to follow authentic research practices, it incites a true feeling of a scientist in them. When the scientific process follows step-by-step, the students begin asking questions to reach fruitful conclusions.

Moreover, by the end of the research activity, their desire for considering future research is well established. As experiments are filled with curiosity, they raise new questions and assist students in thinking about what they can do differently to improve their research. This leads to the development of hypothetical continuation in young students where they hypothesize new questions and combat with ways to test their theories. Hence, a complete research process is implemented, and students gain a thorough understanding of real-world research practices. Another main advantage of SREP is its non-classroom nature which adheres to the importance of extracurricular activities in students. The working instructional model developed by Sikes and Schwartz-Bloom [19] embraces this fact by following a standard 5E (Engage, Explore, Explain, Elaborate, and Evaluate) learning cycle (see Figure 2). Through this paradigm, students extend their learning process beyond the classroom boundaries, gaining more independence in the research and inquiry process. Different studies also verify this aspect and specifically demonstrate this effect on STEM students [38,39]. The majority of the students who showcase strong talent and dedication towards STEM indicate that the reason behind their increased affinity towards STEM is due to non-classroom experiences with extracurricular activities, science fairs, hands-on experiments, nature, astronomy, and so on. Thus, a constructivist learning model like the mentioned above acts as an influential science enrichment program by integrating student exposure to scientific careers in a professional research ambience. Additionally, such a direct involvement by the scientific community in secondary education could help to attract a larger population of students choosing a science career for their higher studies [40,41].

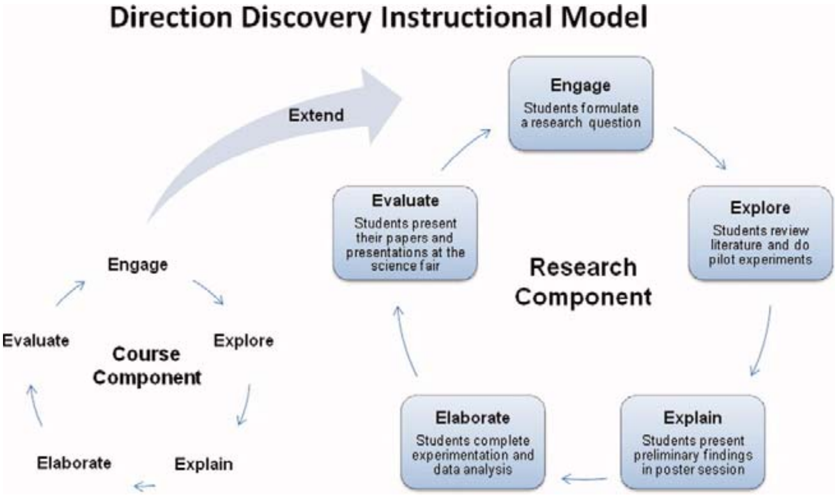


Figure 2. The 5E learning cycle including a course and a research component. The former is performed as an intensive summer course, and the latter takes the form of mentored research project in the following academic year. Reproduced with permission from [19]. Copyright Elsevier, 2009.

In one study by Tai et al. [41], students who pursued research apprenticeships during their high school period were found to have a strong positive correlation to their careers in MD/PhD programs. In fact, the study reported that respondents reporting research exposure in both high school and college time periods were more than four times more likely to pursue MD/PhD program than their peers who never participated in an REP. Figure 3 represents the graphical representation of the estimated probabilities for four sets of categories differing in their REs: (a) Respondents with both high school (HS) and college laboratory research apprenticeship (LRA), (b) Respondents with only HS-LRA, (c) Respondents with only college LRA, and (d) Respondents with no LRA experience. It is clearly noticed that having a LRA significantly affects the persuasion of a doctorate degree. Moreover, in the graph, the area between the curve for both HS and college LRA and only college LRA indicates the important "added value" of HS-LRAs. However, it should be noted here that the level of academic achievement shown in the graph is measured concerning the first attempt score of the respondent in the Medical College Admission Test (MCAT), which provides a measure of their academic performance. This study provides crucial importance of HSREPs, proving that the combined benefits of HS-LRA and college LRA experiences are more effective than only college LRA experiences. Thus, students performing research perceive to show more sophisticated learning processes in STEM fields and are more creative and scientific in their approach towards research. Moreover, the significance of such programs exemplifies the enhancement in high school students' interest in the scientific research process. Their participation in authentic hands-on research experiences could help them develop a cognitive scheme for a research career. In particular, such programs become highly crucial for the students who do not have regular exposure to individuals possessing a STEM background. This is because secondary students get the opportunity to hear success stories directly from those who have experienced research practices before. Therefore, by offering students precollege research experiences, young students can be given enough time, resources, and exposure to gain their research identity and prepare the necessary academic background required for success.

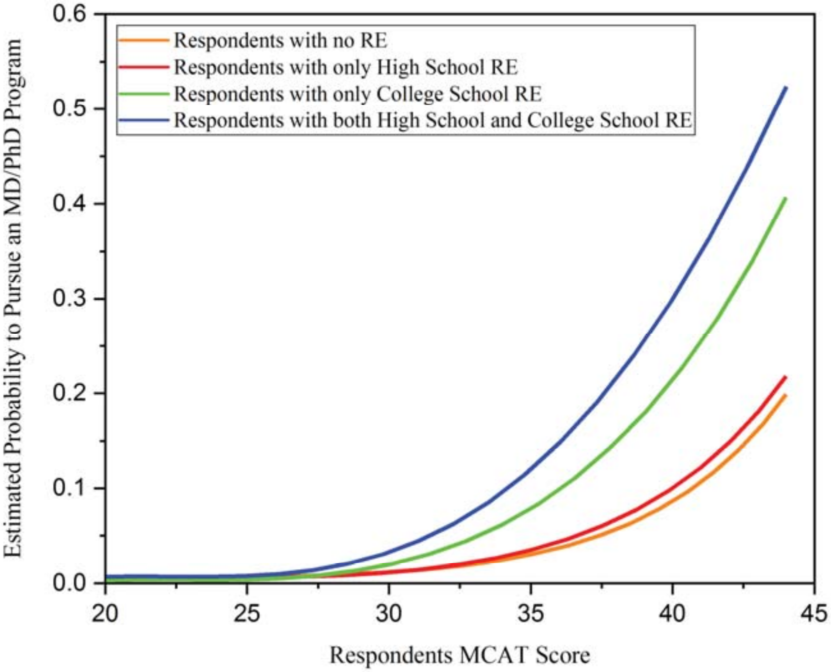


Figure 3. The fitted probabilities of respondents pursuing an MD/PhD program with respect to their Medical College Admission Test (MCAT) scores. Reproduced with permission from [41]. Copyright The American Society for Cell Biology, 2017.

Science pedagogy which is dependent on monotonous learning activities and traditional "cookbook" procedures can contribute to science identity development; still, there is a dire need for authentic REs in today's competitive world which provide a unique self-concept in the student's mind. Research identity thus should be focused more on the authentic practices in HSREPs because these experiences create an understanding of science's novelty and meaningful aspects. The studies discussed in this view, which stick to authentic practices, hint that the participating students perceive a robust increase in their potential to grasp research literacy. This gives the students more personal control over their research individually and allows them to use proper techniques to interpret and understand the research process. Additionally, in authentic research practices in STEM fields, it is recommended to provide students with prior STEM knowledge before entering the program. This way students can be smoothly transitioned towards challenging and complex research practices, eventually refining their skills.

While contemporary SREPs highlight the importance of incorporating authentic REs, educationists have also pioneered collaborative models to strengthen few potent aspects of research. For instance, the necessity of solid mentorship in REs is vital for an enhanced and rightly guided experience for students. The right mentorship allows students to explore their true interests and passion in the subject field. It focuses on their professional skill development during the experience, and in particular: (a) curiosity towards research, (b) ownership and responsibility, (c) ability to accept failure, (d) scientific literacy, (e) professional ethics, (f) collaboration, and (g) real-world consciousness [24]. Thus, mentors can help to create the perfect ground for the evolution of the students into being part of the scientific community. Collaborative models which reinforce the concept of strong mentorship layout frameworks act as a gateway for students to discover their true position and interests in the research field. A guided framework presented by Shoemaker et al. [24] outlines the crucial aspects that students should carefully consider when taking up research practices that best suit their needs and interests. Students should comprehensively understand these essential factors for deciding their research pathway, which include: (a) identifying the discipline of interest, (b) the right timing to start the research, (c) the entry choice of research program (competitive or non-competitive), (d) the goals to accomplish by the research experience, (e) extent of efforts and commitments, and (f) the extent of time they would dedicate to the research. If students structure their entry into research with this mindset, it nurtures their seriousness about research. In addition, it matures them for future academic or corporate sites by exposing them to professionalism and increases their efficacy in STEM learning. Additionally, students who engage in high school opportunities show a robust positive correlation towards pursuing a future STEM degree [42–45]. However, there are limitations faced by collaborative models to implement a highly self-sustainable and effective HSREP meeting all the demands and requirements of a RE. Availability of research-oriented faculty and staff at high schools, along with the costs associated with their training, transportation, resources, and essential logistics, can be a barrier to their efficacy. Establishing an ample human resource of potential mentors to provide research mentorship to students can work best to offer multiple schools and universities within a small-scale location.

The integrated STEM-based HSREPs provide a distinct possibility to influence the socio-cultural values of the school community directly. For instance, the study by Gong and Mohlhenrich [25] found out that their integrated model enabled a unique culture to arise in the high school practices where the investigation and discovery process was highly valued. They observed that this newly emerged culture of research initiated a constructive feedback cycle among the students, enhancing the RE's learning efficacy. Research at the school became more acknowledged and valued. Students showed high levels of motivation to engage themselves in research practices, thus creating a more authentic and meaningful research environment. Therefore, it can be correlated that the culture of research very likely shapes the attitudes and beliefs of self-efficacy among students up to some degree. Moreover, HSREPs need to create a sense of tradition through their programs and stress imparting the significant unique values of research practices in the scientific processes. This is crucial also because when facilitating early access to STEM careers, students should be fostered with persistence and exposed to making strong connections with fellow researchers and mentors [46]. This view connects well with our previous stance on the importance of mentorship in research practices. Therefore, collaborative and integrated models act as a solid backbone to build the professional research community within young scientists exposing them to the STEM career pathway. Lastly, though the benefits of all the models discussed in this review are positive, there is much room for more models to be developed and implemented for high school research.

5. Limitations and Outlook

The discussion presented in this review is limited to a theoretical description (neither precise nor scientific) of the HSREPs reported in the literature. This is because many of the reported studies were performed on relatively small student populations and thus cannot be relied on to make concrete conclusions. This exhibits a pressing need for further studies to experiment on larger student audiences. Additionally, the learning models should be devised in a manner to encourage more students towards research practices, providing more incredible benefits to the educational society. Highly integrated and supportive models for high schoolers need to be reformed to help students decide their research career pathways, inciting their passion for the subject matter.

Moreover, in many countries, STEM-based HSREPs are integrated into classroom experiences through school projects, competitions, workshops of educational administrations, and even curricular subjects. Consequently, many such experiences are unreported, and not much emphasis has been placed on standardizing such REs into systematic research programs at a regional or international level. However, most of the standard HSREPs reported in the literature are from the USA, and thus this review focuses only on such authentic experiences. Therefore, the discussions and conclusions do not certainly apply to the rest of the scientific community.

Some of the studies show an over-reliance on self-reported data. This poses a challenge to synthesize their collective evidence and make concise conclusions on their impact and efficacy. Hence, more work is needed to improve the quality of evidence and establish clear potential benefits of HSREPs in school curriculums. Most importantly, studies should strengthen their claims by using experimental or quasi-experimental designs in their analyses. Data reliability can be increased by deploying control and intervention groups in the study designs. More diligence can be introduced in studies by enabling broader student populations and multiple data sources for reporting student performance. Considerable efforts should be made to use the existing and validated instruments to collect data, thereby building a more coherent evidence base.

6. Conclusions

This review provides insight into the various pedagogical frameworks used for the STEM research experience programs in high schools. It discusses their implications and critical features that impact the student's scientific development. The aim of this review is to gauge the success, challenges, and opportunities of these HSREPs focusing on their effective planning, integration, and influence on high school students. For this, shortlisting criteria were followed to extract relevant from online databases. After their careful examination, the studies were grouped based on their key features and comprehensively studied.

The majority of the studies assessed in this article adhere to the summer version of Research Experience Programs (REPs) which provides a more feasible model for high school students. However, there is diversity in the conceptualization and execution within all the reported programs. While Summer Research Experience Programs (SREPs) offer authentic research practices in students and focus on the overall development of students, collaborative models have been successful in achieving STEM literacy by stressing specific features of research like mentorship, integration, collaboration, and experiential learning. Additionally, integrating school-based STEM research programs into the school culture presents a viable methodology to involve high school students in authentic research experiences.

To sum up, more distinct studies should be performed with customized learning models that can serve students' scientific development apart from the summer models. There seems to exist a lack of reinforcement for schools in offering REPs to students. Authorities and educationists are required to encourage the schools to launch more REPs, and this can reveal unique indications for more effective and sustainable pedagogies that mature students in different aspects of scientific learning.

Author Contributions: Conceptualization, Z.A.; methodology, Z.A. and M.A.; validation, Z.A.; formal analysis, M.A.; writing—original draft preparation, M.A.; writing—review and editing, Z.A. and N.J.A.-T.; supervision, Z.A.; project administration, Z.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Feldman, A.; Divoll, K.; Rogan-Klyve, A. Research education of new scientists: Implications for science teacher education. *J. Res. Sci. Teach.* **2009**, *46*, 442–459. [CrossRef]
2. Leedy, P.D.; Ormrod, J.E. *Practical Research*; Pearson Custom: Saddle River, NJ, USA, 2005; Volume 108.
3. Danch, J.M. The Impact of a High School Research Course on Participants at the Undergraduate, Graduate and Post-Graduate Levels. In Proceedings of the AGU Fall Meeting Abstracts, San Francisco, LA, USA, 9–13 December 2019; p. ED23C-01.
4. Abdelrahman, M.; Yilmaz, M. Best Practices in Creating and Running Research Experience Programs. In Proceedings of the 2012 ASEE Annual Conference & Exposition, San Antonio, TX, USA, 10–13 June 2012; pp. 25.259.1–25.259.16. [CrossRef]
5. Guillen, T.D.; Yilmaz, M.; Garcia, C.A.; Ramirez, D. A K-12 Advanced Research Camp for Engineering and Science Disciplines. In Proceedings of the 2011 ASEE Annual Conference & Exposition, Vancouver, BC, Canada, 26–29 June 2011; pp. 22.49.1–22.49.11. [CrossRef]
6. Swan, A.K.; Inkelas, K.K.; Jones, J.N.; Pretlow, J.; Keller, T.F. The Role of High School Research Experiences in Shaping Students' Research Self-Efficacy and Preparation for Undergraduate Research Participation. *J. First-Year Exp. Stud. Transit.* **2018**, *30*, 103–120.
7. Tai, R.H.; Qi Liu, C.; Maltese, A.V.; Fan, X. Planning early for careers in science. *Science* **2006**, *312*, 1143–1144. [CrossRef]
8. Sadler, T.D.; Burgin, S.; McKinney, L.; Ponjuan, L. Learning science through research apprenticeships: A critical review of the literature. *J. Res. Sci. Teach.* **2010**, *47*, 235–256. [CrossRef]
9. Abd-El-Khalick, F.; Boujaoude, S.; Duschl, R.; Lederman, N.G.; Mamlok-Naaman, R.; Hofstein, A.; Niaz, M.; Treagust, D.; Tuan, H.L. Inquiry in science education: International perspectives. *Sci. Educ.* **2004**, *88*, 397–419. [CrossRef]
10. Hofstein, A.; Navon, O.; Kipnis, M.; Mamlok-Naaman, R. Developing students' ability to ask more and better questions resulting from inquiry-type chemistry laboratories. *J. Res. Sci. Teach.* **2005**, *42*, 791–806. [CrossRef]
11. Neber, H.; Anton, M. Promoting Pre-experimental Activities in High-school Chemistry: Focusing on the role of students' epistemic questions. *Int. J. Sci. Educ.* **2008**, *30*, 1801–1821. [CrossRef]
12. King, D.; Bellocchi, A.; Ritchie, S.M. Making connections: Learning and teaching chemistry in context. *Res. Sci. Educ.* **2008**, *38*, 365–384. [CrossRef]
13. Brownell, S.E.; Kloser, M.J.; Fukami, T.; Shavelson, R. Undergraduate Biology Lab Courses: Comparing the Impact of Traditionally Based "Cookbook" and Authentic Research-Based Courses on Student Lab Experiences. *J. Coll. Sci. Teach.* **2012**, *41*.
14. Spell, R.M.; Guinan, J.A.; Miller, K.R.; Beck, C.W. Redefining authentic research experiences in introductory biology laboratories and barriers to their implementation. *CBE—Life Sci. Educ.* **2014**, *13*, 102–110. [CrossRef] [PubMed]
15. Deemer, E.D.; Ogas, J.P.; Barr, A.C.; Bowdon, R.D.; Hall, M.C.; Paula, S.; Capobianco, B.M.; Lim, S. Scientific Research Identity Development Need Not Wait Until College: Examining the Motivational Impact of a Pre-college Authentic Research Experience. *Res. Sci. Educ.* **2021**, 1–16. [CrossRef]
16. Pfund, C.; Byars-Winston, A.; Branchaw, J.; Hurtado, S.; Eagan, K. Defining attributes and metrics of effective research mentoring relationships. *AIDS Behav.* **2016**, *20*, 238–248. [CrossRef] [PubMed]
17. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
18. Lewis, J.R.; Kotur, M.S.; Butt, O.; Kulcarni, S.; Riley, A.A.; Ferrell, N.; Sullivan, K.D.; Ferrari, M. Biotechnology apprenticeship for secondary-level students: Teaching advanced cell culture techniques for research. *Cell Biol. Educ.* **2002**, *1*, 26–42. [CrossRef] [PubMed]
19. Sikes, S.S.; Schwartz-Bloom, R.D. Direction discovery: A science enrichment program for high school students. *Biochem. Mol. Biol. Educ.* **2009**, *37*, 77–83. [CrossRef]
20. Otterstetter, R.; Buser, S.; Kappler, R.; Herold, K.; Mullet, N.; Mullins, N. A model for collaborative laboratory experiences between higher education and a high school technical preparation program: Promoting higher education, mentoring, and research. *Adv. Physiol. Educ.* **2011**, *35*, 460–463. [CrossRef]

21. Brooks, E.; Dolan, E.; Tax, F. Partnership for Research & Education in Plants (PREP): Involving high school students in authentic research in collaboration with scientists. *Am. Biol. Teach.* **2011**, *73*, 137–142. [CrossRef]
22. Duggan, C.; Cabrera, M.D.; Leger, M.J. Summer Research Programs for High School Students, Supporting Components. In Proceedings of the 2016 ASEE Annual Conference & Exposition, New Orleans, LA, USA, 26 June 2016. [CrossRef]
23. Flowers, S.K.; Beyer, K.M.; Pérez, M.; Jeffe, D.B. Early environmental field research career exploration: An analysis of impacts on precollege apprentices. *CBE—Life Sci. Educ.* **2016**, *15*, ar67. [CrossRef]
24. Shoemaker, S.E.; Thomas, C.; Roberts, T.; Boltz, R. Building a mentorship-based research program focused on individual interests, curiosity, and professional skills at the North Carolina school of science and mathematics. *Gift. Child Today* **2016**, *39*, 191–204. [CrossRef]
25. Gong, X.; Mohlhenrich, E.R. An Integrated Secondary School STEM Research Program: Results, Challenges, and Opportunities. In Proceedings of the 2019 IEEE Integrated STEM Education Conference (ISEC), Princeton, NJ, USA, 16 March 2019; pp. 76–82. [CrossRef]
26. Wang, C.; Vemula, S.; Trevino, J.; Frye, M. Improving High School Girls' 21st Century Skills: Design, Implementation, Assessment on megaGEMS Research Camp. In Proceedings of the 2019 IEEE International Conference on Engineering, Technology and Education (TALE), Yogyakarta, Indonesia, 10–13 December 2019; pp. 1–5. [CrossRef]
27. Leuenberger, W.; Larsen, E.; Leuenberger, J.; Parry, D. Predation on Plasticine Model Caterpillars: Engaging High School Students Using Field-Based Experiential Learning & the Scientific Process. *Am. Biol. Teach.* **2019**, *81*, 334–339. [CrossRef]
28. Oakes, M.D.; Cardella, M.E.; Sydlik, M.; Everett, K.M. Board 41: Developing Summer Research Programs at an NSF ERC: Activities, Assessment, and Adaptation. In Proceedings of the 2019 ASEE Annual Conference & Exposition, Tampa, FL, USA, 15–19 June 2019. [CrossRef]
29. Petersen, J.; Chan, P. A College–High School Collaboration to Support Authentic Microbiology Research. *Am. Biol. Teach.* **2020**, *82*, 201–208. [CrossRef]
30. Gong, X.; Mohlhenrich, E.R. A Comparative Analysis of Secondary School STEM Research Programs in a Chinese School and an American School. In Proceedings of the 2020 IEEE Integrated STEM Education Conference (ISEC), Princeton, NJ, USA, 1 August 2020; pp. 1–8. [CrossRef]
31. Corson, T.W.; Hawkins, S.M.; Sanders, E.; Byram, J.; Cruz, L.-A.; Olson, J.; Speidell, E.; Schnabel, R.; Balaji, A.; Ogbeide, O. Building a virtual summer research experience in cancer for high school and early undergraduate students: Lessons from the COVID-19 pandemic. *BMC Med. Educ.* **2021**, *21*, 422. [CrossRef]
32. Kahn, C.B.; Dreifuss, H.; Teufel-Shone, N.I.; Tutt, M.; McCue, K.; Wilson, J.; Waters, A.-R.; Belin, K.L.; Bauer, M.C. Adapting Summer Education Programs for Navajo Students: Resilient Teamwork. *Front. Sociol.* **2021**, *6*, 1. [CrossRef] [PubMed]
33. Adedokun, O.A.; Parker, L.C.; Childress, A.; Burgess, W.; Adams, R.; Agnew, C.R.; Leary, J.; Knapp, D.; Shields, C.; Lelievre, S. Effect of time on perceived gains from an undergraduate research program. *CBE—Life Sci. Educ.* **2014**, *13*, 139–148. [CrossRef]
34. Thiry, H.; Weston, T.J.; Laursen, S.L.; Hunter, A.-B. The benefits of multi-year research experiences: Differences in novice and experienced students' reported gains from undergraduate research. *CBE—Life Sci. Educ.* **2012**, *11*, 260–272. [CrossRef]
35. Bennett, J.; Dunlop, L.; Knox, K.J.; Reiss, M.J.; Torrance Jenkins, R. Practical independent research projects in science: A synthesis and evaluation of the evidence of impact on high school students. *Int. J. Sci. Educ.* **2018**, *40*, 1755–1773. [CrossRef]
36. Minner, D.D.; Levy, A.J.; Century, J. Inquiry-based science instruction—what is it and does it matter? Results from a research synthesis years 1984 to 2002. *J. Res. Sci. Teach.* **2010**, *47*, 474–496. [CrossRef]
37. Mutlu, A. Evaluation of students' scientific process skills through reflective worksheets in the inquiry-based learning environments. *Reflective Pract.* **2020**, *21*, 271–286. [CrossRef]
38. VanMeter-Adams, A.; Frankenfeld, C.L.; Bases, J.; Espina, V.; Liotta, L.A. Students who demonstrate strong talent and interest in STEM are initially attracted to STEM through extracurricular experiences. *CBE—Life Sci. Educ.* **2014**, *13*, 687–697. [CrossRef] [PubMed]
39. Pender, M.; Marcotte, D.E.; Domingo, M.R.S.; Maton, K.I. The STEM pipeline: The role of summer research experience in minority students' Ph. D. aspirations. *Educ. Policy Anal. Arch.* **2010**, *18*, 1. [CrossRef] [PubMed]
40. Roberts, L.F.; Wassersug, R.J. Does doing scientific research in high school correlate with students staying in science? A half-century retrospective study. *Res. Sci. Educ.* **2009**, *39*, 251–256. [CrossRef]
41. Tai, R.H.; Kong, X.; Mitchell, C.E.; Dabney, K.P.; Read, D.M.; Jeffe, D.B.; Andriole, D.A.; Wathington, H.D. Examining summer laboratory research apprenticeships for high school students as a factor in entry to MD/PhD programs at matriculation. *CBE—Life Sci. Educ.* **2017**, *16*, ar37. [CrossRef]
42. Maltese, A.V.; Tai, R.H. Pipeline persistence: Examining the association of educational experiences with earned degrees in STEM among US students. *Sci. Educ.* **2011**, *95*, 877–907. [CrossRef]
43. Pueyo, N.C.; Raub, A.G.; Jackson, S.; Metz, M.M.; Mount, A.C.; Naughton, K.L.; Eaton, A.L.; Thomas, N.M.; Hastings, P.; Greaves, J. Oxidation of ethidium using TAML activators: A model for high school research performed in partnership with university scientists. *J. Chem. Educ.* **2013**, *90*, 326–331. [CrossRef]
44. Markowitz, D.G. Evaluation of the long-term impact of a university high school summer science program on students' interest and perceived abilities in science. *J. Sci. Educ. Technol.* **2004**, *13*, 395–407. [CrossRef]

45. Gibson, H.L.; Chase, C. Longitudinal impact of an inquiry-based science program on middle school students' attitudes toward science. *Sci. Educ.* **2002**, *86*, 693–705. [CrossRef]
46. Eeds, A.; Vanags, C.; Creamer, J.; Loveless, M.; Dixon, A.; Sperling, H.; McCombs, G.; Robinson, D.; Shepherd, V.L. The school for science and math at Vanderbilt: An innovative research-based program for high school students. *CBE—Life Sci. Educ.* **2014**, *13*, 297–310. [CrossRef]

education sciences

MDPI

Article

Building Improvised Microbial Fuel Cells: A Model Integrated STEM Curriculum for Middle-School Learners in Singapore

Timothy Ter Ming Tan and Yew-Jin Lee *

Natural Sciences and Science Education Academic Group, National Institute of Education, Nanyang Technological University, Singapore 637616, Singapore; timothy.tan@nie.edu.sg
* Correspondence: yewjin.lee@nie.edu.sg

Abstract: The benefits of STEM education for learning important knowledge, skills, and affect are widely accepted, though the former is currently absent in Singapore's formal curriculum. This study therefore describes a model-integrated STEM curriculum at the middle-school level for developing scientific as well engineering literacy. Based on design-based inquiry (DBI), it incorporated inquiry science learning with an engineering design challenge for students to build improvised microbial fuel cells (MFC). Co-planned with science teachers from various disciplines, the curriculum was implemented as a 10-week enrichment program with two groups of Grade 8 students (N = 77) from one secondary school in Singapore. Through the use of vignettes, we show how learning about/of science and engineering occurred in the conceptual, epistemic, and social domains. In addition, students applied evidence-based reasoning, various epistemic skills, and a variety of problem-solving approaches as they iteratively improved their MFC set-ups, which often outperformed commercial kits. This proof-of-concept case study represents the first successful implementation of a STEM-integrated curriculum for middle-school students and can serve as a model for the development of similar programs elsewhere.

Keywords: scientific literacy; engineering literacy; integrated STEM curriculum; microbial fuel cell; design-based inquiry

Citation: Tan, T.T.M.; Lee, Y.-J. Building Improvised Microbial Fuel Cells: A Model Integrated STEM Curriculum for Middle-School Learners in Singapore. *Educ. Sci.* **2022**, *12*, 417. https://doi.org/10.3390/educsci12060417

Academic Editors: Andrea Burrows, Mike Borowczak and James Albright

Received: 31 August 2021
Accepted: 16 June 2022
Published: 18 June 2022

1. Introduction

1.1. STEM Education in Singapore

That science, technology, engineering, and mathematics (STEM) education offers a number of benefits for learning disciplinary knowledge and skills and increases learner interest or affect is not usually disputed. "STEM education" here refers to the general pedagogical approach where there is a conscious attempt to integrate teaching and learning across two or more STEM disciplines, as opposed to a traditional approach, where the focus is almost exclusively on learning in only one of the disciplines during instruction. What remains unresolved are, however, not to be underestimated, including questions regarding what might be the legitimate disciplines that make up STEM, how they are related, and what it means to achieve integration in STEM, among other issues see [1–3]. As science teacher educators from Singapore, what is perhaps more disconcerting to us is that STEM education is a relative latecomer to the local system; it does not appear within the official curriculum and has only recently been offered as part of voluntary, school-based after-school programs for primary and secondary levels [4,5]. Arguably, STEM education is a relatively new construct that is attempting to gain entry in an already crowded science curriculum in this country. For example, there are content-heavy courses in the three major science disciplines (i.e., chemistry, biology, physics) from Grade 9 onwards, while integrated science is taught from Grades 3 to 6 at the primary as well as in Grades 7 and 8 at the middle-school level. This information must also be seen in the light of high-stake examinations at the end of Grade 6 as well as in Grades 10 and 12. With respect to other subjects typically associated with STEM education, mathematics is regarded as an important albeit standalone subject appearing right at the start of formal education at Grade 1, whereas some aspects of engineering education such as its iterative problem-solving nature of design thinking may be located in the subject of Design and Technology that is mandatory for all middle-school students here.

Given this background, where STEM education—not just its component disciplines as standalone school subjects—is just starting to make inroads through the informal curriculum into local schools, we argue that it is timely to showcase a newly created integrated STEM curriculum involving microbial fuel cells (MFC) (explained later). This study functions as a proof-of-concept for local policymakers to show that, with school teachers as partners in planning, it is possible to enable middle-schoolers to experience authentic, complex STEM activities normally reserved for undergraduate students [6]. While this MFC curriculum faced its share of challenges and tensions, we explain that basing it on design-based inquiry (DBI) incorporated inquiry science learning with an engineering design challenge. In the qualitative vignettes in the Results section, we show how the former resulted in students successfully accomplishing a number of measures of integrated STEM learning. For these reasons, we believe that this MFC curriculum can serve as a model for the development of similar integrated STEM programs elsewhere. Our research question that guides the remainder of the paper is thus: what are the affordances for STEM integration and learning through a DBI-based MFC curriculum for middle-school learners in Singapore?

1.2. The Microbial Fuel Cell for STEM Education

Microbial fuel cells can take a wide variety of forms, but are essentially bio-electrochemical devices that produce electricity by tapping on the biological processes of microorganisms [7]. As with any fuel cell, electricity is produced as long as a “fuel” is supplied to it. Typically, small amounts of electrical energy are produced by an MFC, as long as the microorganisms are provided with a source of food (which is its fuel). A scan of the literature suggests that very little work has been done at the pre-collegiate level to employ the MFC in school, let alone develop inquiry-driven experimental protocols, investigate the efficacy of the MFC as a teaching tool, or to determine how it facilitates the learning of science. The few papers have described the MFC as suitable for school contexts due to its “interesting” [8] and “stimulating” [9,10] nature. Despite an attractive feature of incorporating scientific principles from all three natural science disciplines—biology, chemistry, and physics—in its fundamental mode of operation (see Figure 1), relatively little has been written about how this cross-disciplinary intermingling of school science subjects can be capitalized in science education, and there has been even less discussion on the MFC in the context of integrated STEM education.

The paucity of such reports and apparent infrequent use of the MFC in teaching may be due to several factors. Firstly, the MFC remains a somewhat niche area of scientific research. First described by Michael Potter in 1912 [11], the discovery languished for decades because the curious generation of electricity from microbes could not be adequately explained. Briefly considered as an energy source for space travel applications during the space race of the 1960s, current research and development of MFC technology focuses on electricity generation and energy recovery as part of an industrial-scale treatment of municipal sewage and other effluents [12–14]. Smaller-scale applications, such as its potential for powering various electronics, household power generation, and implantable biomedical devices [15], or the use of MFCs as biosensors [16], have also been proposed and are being developed. Outside of the technical research literature, MFCs and other forms of biological fuel cells have only been occasionally cited in popular science articles, typically when used in unusual applications or simply as curiosities. For example, articles have been based on research on the use of urine as a fuel [17], implantable MFCs powered by human saliva [18], and biological fuel cells implanted in rats [19], snails [20], or plants [21].

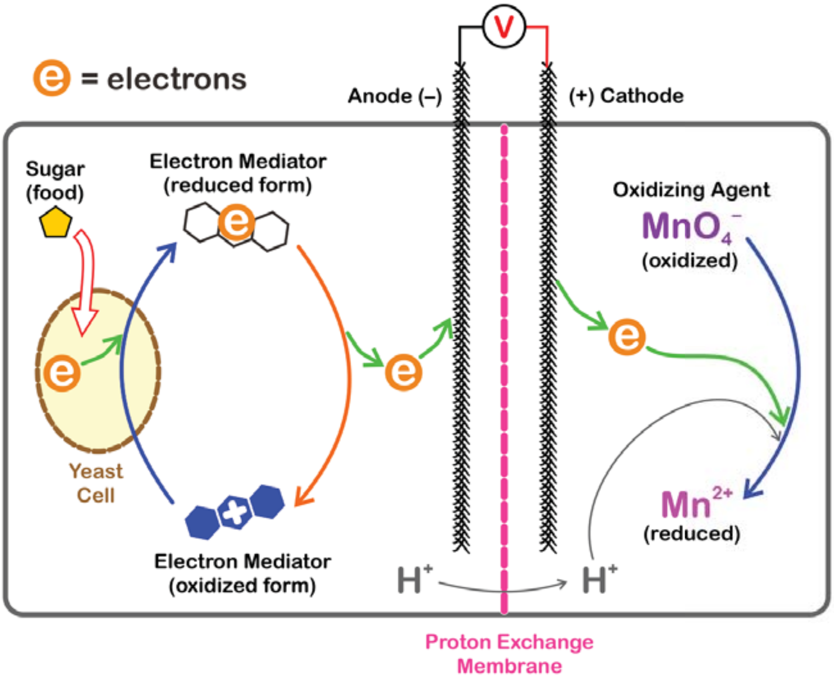


Figure 1. How a simple two-chamber microbial fuel cell works.

Secondly, it is important to note that only miniscule amounts of power can be generated in such smaller scale MFCs, and that they are only suitable for specialized low-power applications. The power produced by tiny MFCs that can be made in school, may be able to illuminate light-emitting diodes (LEDs) and possibly run simple electronic circuits; however, it would not be sufficient to charge a smartphone. Hence, the MFC is not a commonplace technology or device within the everyday experience of most people.

Thirdly, some aspects of the fundamental mechanisms of operation of MFCs remain obscure, even in the technical literature. Designs and operating principles of MFCs are also diverse and generally quite complex. There is a general lack of concise elementary information on the fundamental science behind the MFC, which could make it difficult for an educator to make use of the MFC for teaching, particularly at the pre-collegiate level. This is especially so given that understanding and describing its operation requires broad, cross-disciplinary knowledge across biology, chemistry, and physics. It would be a challenge for an individual teacher to develop the expertise, and even more so to have the pedagogical content knowledge necessary across all the disciplines involved. Because it does not belong within any one discipline, it cannot be neatly pegged into the subject-based curricula so dominant in school systems around the world.

Therefore, the inherently cross-disciplinary nature (mainly science and engineering) of the MFC has hitherto limited its use in the classroom due to a lack of teacher readiness and an appropriate niche in the school curriculum. However, it is this very cross-disciplinary nature that holds much promise for integrative STEM education. There are few, if any, comparable learning activities that intrinsically combine various aspects of biology, chemistry, and physics learning with the opportunity to engage in engineering design tasks. This unique combination is also naturally placed within the context of alternative energy technologies and sustainability issues, which are topical and likely to engage youthful learners. Furthermore, the dearth of accessible "textbook" information on the MFC or its workings, especially for non-experts, makes the MFC very suitable for discovery-based and inquiry-driven learning. It should be clear, then, that the MFC is a very promising STEM teaching tool because it requires learners to actively learn and apply a range of knowledge and skills across science and engineering in the design and iterative refinement of functional prototypes in a manner that more closely resembles real-world work in the scientific and engineering milieu, rather than that of the traditional classroom. In other words, it is more likely to afford the development of authentic scientific and engineering literacy while being more engaging than more conventional curricula.

1.3. Design-Based Inquiry as Pedagogy of Choice

Because using the MFC in school requires knowledge of science content as well as engineering design principles, the pedagogy of choice was design-based inquiry (DBI). It is known by other names, for example, the National Science Teachers Association [22] also refer to it as *Science by Design*. Within science education, DBI was adopted in curriculum packages such as the *Design-Based Science* [23] and *Learning By Design*™ [24].

In DBI, the collaborative construction of an artifact is the driving goal of the activity which activates relevant and just-in-time learning [25–27] rather than heavily frontloading content that occurs in most classrooms. DBI affords agentic learning, where the learner is able to set his or her own goals, as well as present in a classroom context the occasional "dead-end" that scientists typically encounter [28], for example, where designs simply fail to work and/or cannot be made to perform any better due to some inherent limitation. DBI also encourages the application of intellectual reasoning that is often "on the back burner" when teachers say that they are performing an inquiry. Rather than students using a tool in order to learn science prior to applying a technology, in DBI, these processes are intertwined in an ideal case. The DBI approach typically involves setting an initial design problem or challenge for learners to develop or improve upon: for example, designing a mechanically propelled model vehicle that must complete an undulating route, or an assistive device for persons with a disability to lift heavy objects [24]. By working in small groups on authentic real-world design tasks, students perform better on intellectually challenging tasks, develop self-concept and science-based identities, and improve the interaction and communication skills that comprise social literacy [29]. These students also consistently perform measurably better at learning content as well as the science procedural, collaborative, and epistemic skills that are aspects of scientific literacy [29]. For example, students who designed and built working models of the respiratory system were reported to "think more systemically and understand more about the structure and function of human lungs" [30].

A longstanding threat in DBI, however, is the frequent disconnect between the design-goal driven problem-solving and actual conceptual understanding of the science underlying it [29,31]. Some students who had completed DBI projects remained unscientific in their understanding of the underlying concepts [32], or they remained steadfast in their prior scientific beliefs in the face of observed experimental evidence [33]. Relatedly, completion of the artifact might take precedence over the learning, or the authenticity of the tasks may add too much superfluous or confusing material. Special care must be taken to minimize the effect of these pitfalls in the design of the activities.

Incorporating *iteration* into DBI tasks may go some way towards addressing or ameliorating these pitfalls. Requiring students to revisit their findings or improve upon their artifact, especially where the "performance" of the artifact is used to inform the redesign, should provide some impetus for students to "think". It should also remove some of the focus on artifact completion and place emphasis on the development process. Additionally, by breaking the task into iterative steps, problem-solving can be attempted in smaller, less overwhelming chunks. DBI activities naturally afford such iteration as they are typically prone to failure, e.g., failure of prototypes to meet design expectations, naturally requiring further action to correct or adjust for the failure experienced. This type of task iteration is variously described in the *Design-Based Science* "learning cycle" [23] and in the "ritualized activity structures" of *Learning By Design*™ [34], and has been found to be an important feature of DBI [30,35].

We posit *collaboration*, *challenge*, and *competition* as three essential features of DBI-based laboratory activities. DBI-based activities naturally lend themselves to the incorporation of a *challenge*; hence, the grouping of students should be carried out in such a way as to capitalize on this. These challenge goals could be set by the teacher, by consensus at the class-level, or at the group-level. An example goal would be to design and make an MFC that is capable of lighting a high-efficiency LED for 24 h. Students could be organized into persistent groups of perhaps three to five students to work *collaboratively* throughout the MFC activities to attain the challenge goals. The degree of heterogeneity among the group, in terms of ability level, learning style, and so on, would be dependent on the teachers' intended objectives for the program and group dynamics. For example, groups could be intentionally related to mixed-ability, with either fixed or rotating roles within the group. This organization of students into small groups also enables the organization of inter-group *competition* for motivational purposes. The *MFC Challenge* could thus be a *competitive* one between groups. Examples of such a goal would be to design and make an MFC with the highest voltage or with the greatest longevity before falling below some threshold voltage. Organized and managed appropriately, such a *cooperation–competition* instructional strategy can be highly effective for learning [36,37].

The goals for the *MFC Challenge* are introduced to student groups early in the program. The highest voltage of a single MFC from a battery (multiple cells), as well as the ability to light up LEDs with increasing power requirements, the ability to turn a micromotor, and/or the longevity of the MFC, were typical goals [7]. Student groups were free to select the goal(s) they wanted to design towards and later pit their design against other teams. This not only gave students a motivating sense of *agency*, but also required them to make collective design decisions on which goal(s) to focus on, since some goals presented opposing requirements. Building an MFC for a high initial peak voltage tends to have different requirements from those of a long-lasting MFC, while illuminating LEDs tend to require a threshold voltage (via MFCs wired in series), and turning a micromotor requires substantial current (from a battery of MFCs wired in parallel). During the *MFC Challenge*, the MFCs from every group were each tested against all the design goals, and winners could thus be decided for each category.

1.4. Objectives of This Study

The main goals of this work were to develop an integrated STEM curriculum incorporating cross-disciplinary integration of the natural sciences (biology, chemistry, and physics) with collaborative design-based inquiry as a key pedagogical feature for the purpose of developing aspects of scientific and engineering literacy among middle-school learners and to evaluate the curriculum package and the learning that is possible.

The key research question: Can students develop scientific and engineering literacies through learner participation in design-based inquiry using the microbial fuel cell? This was examined using qualitative methods in a case-study approach.

2. Materials and Methods

2.1. Participants

Teachers from a government-aided, mainstream co-educational secondary school in Singapore attending a presentation by the authors expressed interest in the use of the MFC curriculum as the core of a "scientific thinking program" that they were formulating. This was intended as an academic enrichment program for selected lower secondary (middle school) students. A total of 77 Secondary (Grade 8) students in two cohorts (2015 and 2016) were selected by the school for this program. They were generally higher-progress learners with an aptitude for science based on their test scores at the end of Grade 7 and, in some cases, on teachers' recommendations. A total of six teachers were directly involved in the development and implementation of the curriculum—four in each of the two cohorts, with two teachers who were involved in both. In addition, the teacher in charge of the science department had been actively involved in the development of the curriculum. Students were organized into groups of four (three in some groups), where students in a group were typically from the same form class. Groupings were arranged by the teachers involved. For analyses, groups were assigned a letter from A to K (2015 cohort) and L to W (2016), while students were given a pseudonym beginning with the group letter. The letters I, Q, and U were skipped in the group names for easier naming of student pseudonyms.

The research team consisted of the authors who are education faculty members. At the time of the first cohort, T.T.M.T. had 12 years' experience as a science and technology teacher-trainer, which included five years as a science education researcher, while Y.-J.L. had 16 years' experience as a professor of science education and eight years prior experience as a school science teacher.

2.2. Development and Implementation of the Curriculum Package

The structure of the MFC curriculum (see Table 1) was conceptualized to consist of ten weekly sessions in four phases: introduction, experimentation, design-based inquiry, and consolidation, in order to provide a runway for students to engage in iterative experimentation and prototyping in a learning progression from guided to more open inquiry learning approaches. Details of the MFCs used as well as the key parameters suitable for student-led experimental investigation and for which design choices need to be made when constructing their own improvised MFCs can be found in Appendix A. The final implemented curriculum was co-developed with experienced science teachers from the cooperating school, and was further refined between the implementations with the first and second cohorts. The teachers contributed in the creation of structured worksheets, the adaptation of instructional materials to suit their own teaching, conduct, and facilitation of sessions, as well as in the overall refinement into a complete curriculum package.

Implementation of the MFC curriculum was enacted by the teachers involved with the authors present as research observers and were, on occasion, called to answer questions or provide technical expertise to teachers or students directly. In each session, there were typically several teachers present, with at least one teacher with disciplinary background in each of the natural sciences of biology, chemistry, and physics. The Introduction phase was conducted in a standard classroom through direct instruction in requisite prior knowledge and skills in biology, chemistry, and physics topics by the teachers with relevant expertise. Teachers were also assigned to mentor two to three groups of four students each during the Experimentation and DBI phases, which were conducted in a standard school science laboratory. The teachers monitored and facilitated group planning, discussion, and conduct of experiments and prototype construction, mainly by answering students' queries and prompting them with questions, while avoiding directly influencing student actions or decisions. Immediately after each session, the teaching team and research team conducted a debrief, where mutual feedback on any instructional stints and learning points were shared, and where teachers had the opportunity to collect answers on "difficult" questions they or their students had. General administrative, lesson planning, and logistical matters for the next session were also discussed.

The MFC curriculum has been implemented with slight variations and allocations of time spent in each phase. In this study with Grade 8 students, each session averaged two hours each. The curriculum program consisted of a total of nine or ten sessions, typically once a week, though with interruptions for holidays or other activities. Consolidation of learning was originally conceived as a combination of group-based project reports and presentations to emulate the professional communication and sharing of findings that are a part of scientific and engineering practice. However, this was not always done due to a lack of time.

Table 1. Outline of the MFC Curriculum.

Phase	Learning Activities	Timeframe
Introduction	• Lessons on required prior knowledge ○ content/conceptual knowledge ○ practices, procedural skills, e.g., designing and conducting experimental investigations ○ introduction to the *MFC Challenge*	1–2 sessions
Experimentation	• Guided and open inquiry ○ conduct experimental investigations to determine effect of varying type and parameters of key MFC components/properties ○ sharing of experimental data as a class ○ analysis of each round of collective experimental data to formulate design of subsequent experimental investigation	3–4 sessions
Design-based Inquiry	• Iterative design and construction of MFC prototypes ○ engineering-design, 'making' and problem-solving ○ measurement of MFC prototype performance characteristics ○ intergroup observations of design ideas, construction techniques and success/failure outcomes	3–4 sessions
Consolidation	• MFC Challenge competition ○ Performance of MFC prototypes measured for each challenge criteria ○ Awarding of prizes ○ Consolidation of learning	1–2 sessions

2.3. Problem-Solving as a Measure of Scientific and Engineering Literacy Development

The aim of the MFC curriculum program was to contribute to the development of scientific and engineering literacy by engaging learners in inquiry-driven cross-disciplinary STEM tasks centered on a design-based challenge. The principal research task in evaluating the MFC curriculum was thus to examine the *development of scientific and engineering literacy* over the course of the program. To limit the scope of the research, *problem-solving* (PS) was chosen as the aspect of scientific and engineering literacy to be studied and to serve as a gauge for the development of it. Firstly, for a program pedagogically anchored in the problem-based learning paradigm, there was the inherent and ubiquitous need to *solve problems* that were posed and encountered throughout the program. This meant ample affordances and opportunities to observe PS as a central activity, and also one that is of value as a topic of research, with PS being a skill ubiquitously touted as an important competency in the present and future world. Secondly, there has been relatively little study of learning outcomes in integrated science curricula other than for science *content* knowledge [38], even where engineering design-based activities were conducted [39,40], which suggested an opportunity for research. Thirdly, the authors were interested in the ability of individuals to apply pre-existing knowledge, especially science knowledge learned in school and any nascent engineering skills, in the service of overcoming an encountered *problem*. The MFC curriculum was thus positioned as a means to expose learners to and exercise them in the applied use of the science and engineering knowledge they have, and perhaps then to seek the necessary knowledge they do not yet possess—that is to say, a means to engage in inquiry-based learning. To examine PS is thus to examine learners engaging in integrative cross-disciplinary, inquiry-based learning and, in the process, to develop aspects of scientific and engineering literacies.

Therefore, there is a selective focus here on the use and cultivation of PS skills for the development of these literacies, and in particular on the *overall* process of "finding a solution" to a problem—*not* in the underlying psychological constructs, task translation, or other cognitive processes in the development of the solution. The approach of Klahr and Dunbar [41] in framing PS as a "dual-space search" is particularly useful in this respect. In this model, PS is characterized as the application of *scientific reasoning* in a search process for answers in both a "hypothesis space" and an "experiment space". In the former, the learner scans their prior knowledge to generate explanations, while, in the latter, they may test ideas and seek results through experimentation in the real-world, ultimately to apply both these strategies towards finding or constructing a solution to the particular "problem". Both these aspects are important in this project, where it is hoped that students would apply their scientific knowledge to PS, as well as apply themselves to the conduct of suitable investigative practical work to derive answers and solutions to meet the design goals set, and similarly for the engineering design task of building MFC prototypes and thereby exercise themselves towards the desired scientific and engineering literacy goals. These two approaches to PS could be suitably described as fitting an *engineering model* or *science model* of experimentation, as framed by Schauble et al. [33]. Fundamentally, a science model of experimentation establishes as its goal to understand the "relations between cause and effect", whereas an engineering model seeks to "make a desired or interesting outcome occur or reoccur" [33] (p. 861). They further distinguish between the two models in the approaches that students adopt in practical work, where an "engineering" approach tends to focus on manipulating variables to produce a desired outcome, and when that outcome or some approximation of it is achieved, the experimentation stops—a try-and-see approach. On the other hand, a "scientific" approach attempts to systematically test all possible combinations of variables in order to derive the underlying principles and relationships of the system—a more theory-laden approach. Katehi et al. succinctly describe this distinction as "scientists investigate and engineers create" [31] (p. 41), while Apedoe and Schunn [42] usefully describe these as "science reasoning" and "design-focused" approaches.

2.4. Data Collection

Lessons were video- and audio-recorded, with audio recorders placed on each group's laboratory bench to capture group discussions. Typically, three video cameras were positioned around the science laboratory, each covering nearly the entire room in wide angle. An additional three video cameras were placed so as to focus on selected groups and/or provide additional views of the laboratory. Based on teachers' recommendations and the research team's observations during the initial lessons, two or three groups in each cohort were chosen for closer observation based on their potential for richer and more varied interactions. Video and audio recordings were assembled into synchronized multi-camera views using Final Cut Pro video editing software. Interactions and discussions could generally be followed by switching to the most appropriate camera view and audio track from the closest audio recorder. Notes of key events and noteworthy interactions mapped to the video timeline were made as a form of indexing of the data. Field notes from the direct observation of and interaction with students by the research team (primarily T.T.M.T.) of student actions and discourse were later cross-referenced and analyzed in conjunction with the lesson recordings in order to produce vignettes. In addition, group and individual worksheets (containing experimental data, design sketches, responses to guiding, assessment or survey questions) were collected, while still and video images of student prototypes were recorded. Video-recorded focus group discussions of about one hour with selected students (typically one from each group) were conducted within a week after each cohort concluded the program.

2.5. Analysis of Data

Our method of qualitative analysis followed Barton et al. [43], who themselves based their own analysis on ethnography and grounded theory. These authors first located individual episodes of interest within longer periods of field work in the science classroom. By so doing, they wished to understand how separate events contributed towards overall trends in the learning and engagement of students over time. Taking such a dual perspective of events and time therefore "worked in a complementary fashion to inform on the girls' contextually situated merging practices and identities" [43] (p. 81). While these authors represented their findings based on three specific practices, we decided to adopt a similar method of qualitative representation based on vignettes [44]. It was also because the MFC curriculum was a complex, multi-week intervention, that we have chosen to describe our findings through the use of three vignettes. Vignettes as qualitative representations are ideal here because they "restructure the complex dimensions of the subject for the purpose of capturing, in a brief portrayal, what has been learned over a period of time" [45] (p. 70). Employing a narrative format that is based on fact/evidence, they are "composites that encapsulate what the researcher finds through the fieldwork" [45] (p. 70). Furthermore, the analysis of vignettes serve as a strategy for contextualizing the data and as a means to find the relationships and connections therein [46]. These vignettes thus summarize and portray aspects of the lived experience of the participants in this program, their interactions with the semi-structured learning activities, and with each other, in order to illustrate the potential for learning afforded by this multifaceted intervention. Vignette analysis was supplemented by and triangulated against analyses of student artefacts (worksheet answers, design sketches) and focus-group discussions.

As earlier described, there was a particular focus on revealing instances of PS at the individual student as well as group levels, and the patterns of underlying conceptual and epistemic approaches (i.e., "scientific" or "engineering") adopted that apparently influence such PS. A set of descriptors for each approach was drafted in general alignment with Schauble et al. [33] and adapted for the context of this program, supplemented with exemplifying statements sampled from written artefacts and transcribed student discussions. These descriptors were used heuristically to determine the approaches adopted in particular instances on a best-fit and consensus basis between the authors.

Other qualitative and semi-quantitative evaluations of the curriculum package and its implementation, as well as its impact on student interest and engagement, were separately conducted and not presented here in order to focus on the key research question.

3. Results

To answer the research question, descriptions of three student groups, as well as selected pseudonymized students within each group, their actions, and discourse, are presented here for illustration. In general, it was observed that groups that were less successful (less robust prototypes and/or lower voltage, or even non-functional prototypes) tended to approach PS with a narrow focus. Either an overwhelming emphasis on the "science" or else that of being "practical" or on the "making" without appropriately establishing optimal or even just workable parameters. More successful groups tended to have heterogeneous opinions in their discussions and arguments, approaches to problem-solving, and generally had to compromise between opposing ideas; however, in so doing, seemed to give rise to more effective solutions. The first two vignettes are from groups that exhibited a bias towards either an overwhelmingly scientific (Group E) or engineering (Group G) approach.

3.1. Edwin and Group E

> A personable, smiling, and polite student, Edwin was obviously well-liked and respected by his group members. The teachers had very positive impressions of him and thought of him as intelligent and good at science. I remember him as being quick to offer thoughts and explanations using reasoned and scientific ideas. In the very first session of the DBI phase, Group E had made a prototype

that produced a very high voltage, the highest among the groups that completed a prototype that week and an impressive 0.832 V—on their first try! Part of this success came from their choice of reagents to use in this prototype, which they had decided upon based on their earlier excellent investigative experimentation using the Bennetto cells. This immediately gave Group E a certain reputation for "scientific" prowess within the class. In subsequent weeks, other students would "drop by" the group's bench to "check out" their progress. One obvious problem with their first prototype was that it leaked. This was a problem for nearly all groups; however, theirs was obvious. This "design flaw" may have been the major push factor for them to attempt a very different design approach with their next prototype. However, there were other reasons too. Edwin kept detailed notes in Group Worksheet 1 in his file. In it, he had reasoned that they could obtain even better performance if their next design had a larger surface area of the cellophane membrane; have a larger volume; and, to "shorten the distance" between the two chambers by removing the bridging tube, hence leading to the design of the second prototype (see Figure 2).

The second prototype had a maximum of only 0.632 V, lower than the first. Inter-chamber leaks were noted and reasoned to be the cause of the lower voltage. The next session, the design changed to reduce chamber volume (partly from the teachers' calls to consider and reduce volume where possible to save on the amount of chemicals used), with a focus on a larger ratio of membrane surface area to chamber volume. They also returned to the use of carbon-fiber for the electrodes, after it had been suggested (not clear by whom) that the use of rods in the second prototype reduced surface area and that the general consensus in the class was that fiber electrodes were "better". This third design achieved a high maximum of 0.845 V, which I pointed out was a "record" at the time. Group E was the odds-on favorite to win the MFC Challenge the following week. However, the same problem with leakage was plaguing this design. Regardless, it was decided to make more of the same for the Challenge. By the Challenge session, Group E had four nearly identical units of their third design. However, testing with water showed multiple leaks, and there was no easy way to reach the inner joins of the membrane and chambers due to its shape. They tried various ways to plug the leaks with epoxy glue, hot-glue, and tape, but nothing worked. They filled the prototypes anyway and put them forward for testing. The highest among the four tested at only 0.130 V at the time of the single-MFC challenge. By the time of the battery challenge, none had any appreciable voltage, and, in any case, most of the chemicals had leaked out. It was a huge disappointment, not just for the group, but it seemed even among the other groups, that Group E had not succeeded.

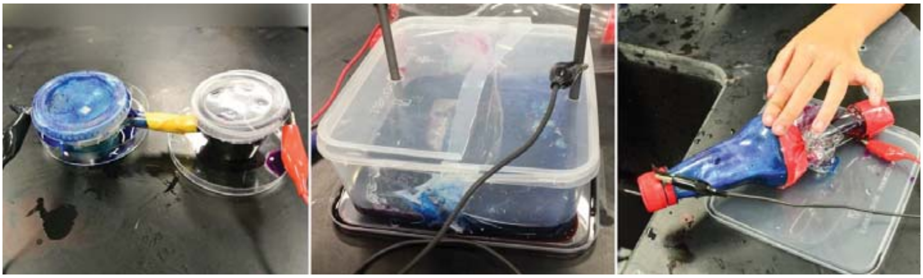


Figure 2. MFC Prototypes by Group E. From left to right: First, second and third prototypes. The third design was used for the MFC Challenge, where a total of four identical units were made.

3.2. Gerald and Group G

A quiet, soft-spoken student with a constant dour expression, Gerald had difficulty interacting with classmates and generally avoided having to do so. In his interactions with teachers and me, he seemed to be full of ideas, which he sometimes found difficult to express, but also seemed to be "resistant" to our explanations and answers to his questions, especially when they conflicted with the conceptions that he held. Group G was one of three groups that only had three members instead of four. According to the teachers, Gerald, Gloria, and Gwen were not on friendly terms with each other, and, in the MFC program, Gloria and Gwen were forced to be "friends" by their common dislike and distrust of Gerald. These circumstances largely explain the extremely dysfunctional dynamics of the group. Progress every week was slow, discussions were mostly between Gloria and Gwen only, but these were not particularly productive. During this first half of the program, Gerald would occasionally approach me directly to ask if he could see me "later". However, at the end of the lesson, he would quickly leave, claiming that he had "tuition" (lessons by private tutor). On one or two occasions, I managed to find the time to talk with Gerald about his questions. He was intensely interested in how the MFCs worked, and what use they could be put to. He had obviously read various material online and had somewhat convoluted ideas that he wanted to incorporate into "his" designs for the DBI phase. These ideas, however, were fundamental misapplications of misunderstood concepts. It was hard enough to know where to begin explaining why they were so, but even more so because Gerald seemed to become upset when I tried to do so.

At the first DBI session, Gerald brought along a plastic carrier bag from which he revealed a clear plastic "biscuit" container with a red screw cover (can be partly seen in Figure 3, indicated by arrow). It contained a brown slurry, and a pungent smell emanated from it. A teacher asked him what it was, and he explained that he had made it at home, based on information gleaned from the internet. He had filled it with leftover food the week before, and left it to "ferment". He showed that it registered a voltage. His groupmates and the teacher were revolted. When I was made aware of it, I too was shocked, but curious that it "worked", I asked him to explain how it did so. Rather than engage in talk, he showed me two sheets of paper with dense printed text describing a long protocol. It became evident that dissimilar metal electrodes had been used, and this accounted for the voltage, it was functioning as a galvanic cell, not as a fuel cell. I tried to explain this to Gerald, but as always, he did not accept what I said. I asked where the protocol came from, and, as best I could understand him, it seemed he had concocted it from at least two sources, essentially combining some instructions to build a conventional galvanic cell, with some (presumably) research article for a single-chamber sludge-based MFC. The former being a "modification", since he did not quite understand the way the latter had to be built. It was, however, very well-made. Neat, carefully-crafted parts. The teacher and I told the group that it was not an MFC, and hence they should proceed with construction of another. The two girls had brought some plastic bottles and all three students reluctantly got to work, though it was almost entirely the work of the two girls. Gerald spent a lot time just staring into space or aimlessly moving about. The prototype leaked badly and did not register a voltage, which may have been due to the poor design, resulting in the liquids not coming in contact across the small piece of membrane at one end of the bridging straw. Since that lesson, Gerald had repeatedly turned down all offers to have a chat or for me to answer his questions. He was polite, but the distinct impression was that he no longer wished to interact with me.

The following week, Gerald was unable to attend the lesson, but had a large plastic carrier bag delivered to class with another of his made-at-home MFCs.

> Made with the same type of plastic container as the first one, this was similar in design to the one made by Gloria and Gwen, but very sturdy, fully watertight, and most of all, really large. This led to problems with filling it. Both "chambers" were excessively large, perhaps a liter each. Gloria and Gwen were quite stunned at the size of the MFC and quickly realized that they would not have enough reagents to fill it. Even when all the chemicals were put in, they did not reach the level of the tube that bridged the chambers. The two girls debated, consulted their teacher, myself, and possibly asked friends from other groups. They were reluctant to build a new, smaller MFC (my suggestion). A seed of an idea to displace volume—just like in Aesop's Crow and the Pitcher—arose somehow, but they could not find suitable types and quantities of materials to put into the chambers. Eventually, they hit on the idea to inflate latex gloves to fill the chambers and hence raise the liquid level to fill the bridging tube. However, no record of the voltage obtained was made.
>
> For unknown reasons, Gerald did not bring an MFC prototype to the MFC Challenge session. Instead, the two girls were trying to make two MFCs, using plastic bottles and containers, some of which were apparently unneeded parts from other groups. Given the limited time to build during that session, they did not complete the MFCs in time to participate.

Both Groups E and G were unable to field properly functioning MFCs at the appointed time for the MFC Challenge. During earlier Experimentation sessions, Group E had shown great promise, achieving good performance characteristics in their prototypes through careful, systematic experimentation and analysis of findings to select reagents and conditions. Group G suffered from a dysfunctional group dynamic; however, all three members had demonstrated excellent practical engineering skills. Gerald had constructed well-made prototypes, while Gloria and Gwen were able to find ingenious ways to displace volume with the limited resources available. Both groups demonstrated notable strength in either scientific or engineering ability, but a concomitant weakness in the other area. Group E members excelled in conducting and analyzing controlled experiments but lacked the engineering skills to build watertight prototypes. Conversely, Group G had those skills but lacked the correct scientific conceptions, had persistently clung to beliefs in the face of contrary evidence or explanations, and had kept little to no record of their experimental data.

Figure 3. MFC prototypes by Group G. From left to right: first prototype, arrow indicates "fermentation MFC" made by Gerald at home and brought to class; second prototype made at home by Gerald, with inflated latex gloves and pebbles used to displace volume; incomplete third prototype made during final MFC Challenge session.

In comparison, Group N was one of the most successful groups. They attained a voltage of 0.847 V in the MFC Challenge and, although their final prototypes leaked, they were able to problem-solve quickly to staunch most of the leaks and managed to keep their MFCs functioning. An examination of their individual approaches to PS, their group dynamic, and how this resulted in a combinatorial approach to PS, suggests that their success can at least be partially attributed to the confluence and application of both scientific and engineering approaches.

3.3. Group N: Diverse but Effective

The four students of Group N have distinct approaches to encountered problems. Nigel tended to focus on data and evidence, just like Naomi, but he preferred to develop his own data empirically and formulate his own conclusions rather than rely on that of others, whereas Naomi would endlessly pore over the collective data from all the groups, comparing and trying to spot trends or some clue as to the best choice to make for the next experiment or design iteration. Both of them clearly foreground a scientific approach in both the experimentation and DBI phases. On the other hand, the other two members tended towards engineering-like methods, seeking options that were at least workable, and doing so either from gut-feel, or else copying and perhaps adapting from existing information or design ideas. Nellie tended to take the "easy" way out, namely the closest approximation or simplest approach. Noella was more circumspect and would consider data, and was willing to accept the data at face-value (unlike Naomi's deep deliberation). She primarily focused on using what was already "known" as a basis to "move on and try the next thing". The following exchange between group members illustrates this.

Group N is again trying to decide what chemicals to use in their first MFC prototype. The discussion is centered on whether they should use a mixture of the two oxidizing agents, potassium manganate (VII) and potassium hexacyanoferrate (III), as the catholyte in their prototype. The shared data from the previous session revealed that Group W had attempted that combination and obtained a significantly higher voltage compared to using either of the oxidizing agents alone. The three girls want to use the combined catholyte, but Nigel is opposed to it.

Nigel: It's proven one time only eh . . .

Nellie: Nigel! (in exasperation)

Noella: Trust the freakin' results! (in exasperation)

Naomi: Try it now? I mean we can try it now. So that next week can confirm. (calmly)

Noella argued that they could try it this one time, and if it did not work, they would not do it the following week. However, Nigel said that trying this combination of oxidizing agents would mean they were changing two variables, namely the prototype design and the catholyte chemistry. Noella argued that "the cell everybody changes! Everyone's still trying something . . . ", but Nigel insisted that they should stay with the catholyte parameters determined from their own experimentation and only vary the cell (prototype) designs henceforth, so that the prototype designs can be directly compared to see which developed the highest voltage, "these few weeks we are meant to upgrade the cell, not change the chemical. If we keep changing the chemicals, then we won't know how to improve the cell!". The three girls expressed frustration and jointly confronted Nigel: Naomi tried to reason with Nigel, "But you see, we can see whether this one is better or previous one is better."; Nellie pleaded, "Okay, just do this one?"; and Noella glared, "It's three versus one, majority wins!". Nigel, unfazed, just retorted, "but logic wins!"

Nigel was steadfast in his strict interpretation of the "fair test" methodology (that is, only one variable at a time is varied in any experiment). He was concerned

> with being able to compare the differences brought about by each iteration of their cell design. Noella and Nellie were more concerned about the limited time and opportunity to derive the best possible MFC design and chemistry. While Nellie wanted to "just do it" or "just do it this once" in the interests of expediency, Noella's argumentation involved references to "everyone else" doing the same, and decision-making by the "majority". However, it should be noted that their approach was not borne of a slipshod attitude. Indeed, the two were the most industrious and would do most of the 'making' during DBI. Naomi used reasoning and data to respond to Nigel's "logic"—that the current week's experiment could still be compared (or "confirmed") the following week, or against the previous iteration.
>
> Later, while Noella and Nellie were trying to cut their carbon-tissue electrodes, there was a lot of discussion on the size and placement of the holes through which the electrodes would be inserted, and the size and shape of the electrodes themselves. Nigel wanted them "short" but "wide" to have a short electrical path, but maximum surface area in contact with the chemicals. Noella kept emphasizing the difficulties this presented in getting the electrodes inserted and may have been suggesting carbon rods to be easier to insert (albeit at the expense of electrode surface area). Eventually, Nigel suggested a compromise: to cut a slit instead of a drilled hole to fit the electrode, and this worked well from both prototype construction and effective design perspectives. The net result arose from the combined input of group members, each adopting contrasting approaches, both scientific and engineering.

It was interesting that most students were observed to persistently and consistently adopt their particular approaches to assessing, prioritizing, and addressing the multiple scientific and engineering problems encountered in the MFC curriculum. The four members of Group N were a microcosm of the general approaches seen. Some students such as Naomi and Nigel focused on "scientific" decision-making; however, where Nigel prized a logical and first-principles approach and trusted only empirical data from personally conducted experimentation, Naomi looked towards systematic analysis and a consideration of *all* available data in a search for trends to lend weight to the "correct" decision. On the other hand, Nellie and Noella adopted "engineering" approaches, as generally defined by Schauble and colleagues [33]; where Nellie preferred to seek the first functional solution that minimally suffices, Noella tended to reference known solutions and/or seek "a better way" to achieve something. These four approaches could be seen as distinct epistemic stances to PS, and we are developing a taxonomic framework to classify and describe these epistemic stances or approaches adopted by learners in problem-solving tasks encountered in integrated STEM problem-based learning activities [47].

The interpersonal interactions within Group N may have appeared slightly combative and heated at times, with members expressing frustration with each other's approaches to the tasks at hand. However, unlike the negative attitudes, lack of trust, and communication seen in Group G, Group N members were ultimately united in their goal to do well as a group in the MFC Challenge. Group N's within-group discussions were energetic and vociferous at times, but it seemed to be based on a mutual drive to *persuade* each other to their viewpoint, and a level of mutual respect to compromise and reach a tacit or even reluctant consensus for important decisions. The group's progress could thus be seen in part as a product of the push–pull between the individual members' approaches to PS. This ability to compromise was in sharp contrast to two other groups (P and V, not shown here) where the group dynamic was skewed by one domineering member insisting on doing things "their way". Both these groups fared poorly in the MFC Challenge.

4. Discussion

We now summarize the findings that support our claim that building improvised Microbial fuel cells are a model-integrated STEM curriculum for middle-school learners in

Singapore. Specifically, we discuss its affordances in terms of: the development of a STEM Curriculum Package (Section 4.1); problem solving and students' conceptual and epistemic knowledge gains (Section 4.2); group composition and performance (Section 4.3); before we describe some of its potential significance and impact (Section 4.4).

4.1. Development of a STEM Curriculum Package

The MFC curriculum presents a way to effectively integrate learning across STEM domains, especially in science and engineering. In engaging learners with a linked set of activities that progressively present a series of problems to be solved (what reagent to use, what concentration of reagent, what design features to incorporate, etc.), learners may learn concepts and skills, and, perhaps more importantly, are often forced to apply that newfound knowledge or skill in combination with prior knowledge as well as the ideas and opinions of their group members in the service of achieving the designated challenge goals. The vignettes presented above illustrate the how the MFC curriculum can engender and bring about such learning.

As described in Section 1, the MFC curriculum has certain disadvantages, primarily in the logistics/cost, and, perhaps more significantly, in its need for sufficient curriculum time, teacher readiness, and, in essence, a willingness by school leadership to embark on a curriculum program that is not focused on preparation for traditional academic achievement tests. Others are perhaps yet to be swayed to do so because further work lies ahead for this nascent and niche curriculum in order to produce evidentiary validation of our claimed merits. To that end, our future work will seek to further codify the learning that is possible, aided in part by a novel taxonomic framework in development, as well as to determine implementation success factors for the MFC curriculum and similar programs.

4.2. Problem Solving and Students' Conceptual and Epistemic Knowledge Gains

Problem solving was selected as a measure of the scientific and engineering literacies we were interested in since there are many opportunities to observe PS in the type of problem-based learning activities presented here. Were students able to solve the problems encountered through the application of conceptual knowledge and skills, either acquired prior to or during the MFC curriculum? This was clearly true when looking at PS in specific tasks by specific students. Students were able to find solutions to problems encountered as well as make design decisions, in terms of experimental design or engineering design, based on reference and/or empirical data. Were students able to demonstrate and apply different epistemic approaches to PS? Some students excelled at the designing of experimentation of physical prototypes, others at finding optimal conditions from detailed analyses of data or for optimal and efficient ways to construct some item. However, as might be expected, no individual student appeared to be broadly proficient in all areas. Nonetheless, it can be seen that Edwin, Naomi, and Nigel demonstrated proficient scientific abilities, while Gerald, Gloria, Gwen, Nellie, and Noella demonstrated impressive engineering prowess. While these were selected individual examples, they were not isolated cases. Other students (not shown here) had exhibited varying degrees of proficiencies and, indeed, in some instances, were possibly even more impressive.

At the individual level, these gains may be concentrated in either of, rather than both, domains of literacy. As earlier described, individual students tended to adopt relatively specific and consistent approaches to PS, being either distinctly "scientific" or "engineering" stances, as exemplified by each of the four students from Group N. Whether these epistemic stances represent existing aptitudes and/or were encouraged and developed by the activities presented by the MFC curriculum remains the subject of further study, as is the taxonomic framework we are developing for this purpose. Regardless, if the MFC curriculum is able to develop or at least proffer the opportunities for individual students to exercise their scientific *or* engineering knowledge and skills, then it should be able to do the same for all learners to some degree, whether they tend towards scientific or engineering stances. In other words, even if a student's tendency to adopt a "scientific" stance is somehow an innate inclination, they would still be exposed and have opportunities to develop *both* their scientific and engineering literacies in this integrative curriculum. It is perhaps of interest from a learning science perspective that the MFC program also affords a platform for the observation and further study of such epistemic approaches by learners.

The development of PS and other aspects of scientific and engineering literacies in science-based and/or engineering design-based inquiry learning activities have also been reported in other studies. These are summarized in Table 2 along with their relevance to this study. Our findings and those of these studies broadly agree with and complement each other.

Table 2. Comparison of Findings with Other Studies.

Study and Key Findings	**Implications for MFC Curriculum**
Wendell and Rogers (2013) [39] From an experimental study of an engineering DBI curriculum for elementary students, it was found that learners gained science content knowledge as well as engineering design skills that were independent of increases in attitudes towards science among learners which may arise due to the novelty of the curriculum.	Engineering DBI offers the potential to develop desirable science and engineering literacies, even if they often increase attitudes towards science for other reasons.
Fortus et al. (2004) [23] Science knowledge as well as problem-solving skills were significantly improved among 9th graders undergoing three cycles of DBI. Learning gains were assessed by pre-post written tests, and with models and posters to check application of knowledge to design problems.	Science-based DBI does also appear to support problem-solving skills.
Marulcu and Barnett (2015) [40] In a mixed-methods comparison of an engineering design-based curriculum with a FOSS inquiry program on simple machines for 5th graders, both approaches significantly improved their science content knowledge. However, learners in the DBI approach performed significantly better on the interview questions.	Engineering DBI is neither superior nor inferior to other forms of inquiry-based learning.
Li et al. (2016) [48] An engineering design-based modeling approach with LEGO helped 4th graders in their science content knowledge as much as those in the control group who learnt by inquiry. However, pupil gains in the experimental group were significantly higher for problem-solving ability ascertained through a survey questionnaire and evaluation of physical artifacts.	Engineering DBI does appear to support development of problem-solving skills and science content knowledge.
Shanta and Wells (2020) [49] Through an authentic engineering design-no-make challenge, high school students demonstrated significantly better critical thinking and problem-solving abilities compared to traditional classroom instruction.	Engineering DBI does again appear to support development of problem-solving skills.

4.3. Group Composition and Performance

Beyond the individual learner's development of scientific and engineering knowledge, skillsets, and overall literacies, it was apparent that success with DBI tasks at the *group* level somewhat depended upon group composition and the interactions between its members. Leaving aside the general dysfunction of group dynamics arising from interpersonal issues, and viewed through the perspective of this study's focus on PS, we found that groups that consisted entirely of students with the same overall conceptual and epistemic approach to PS (either "scientific" or "engineering") such as Groups E and G, or where one individual's will dominated (Groups P and V), were the most likely to fare poorly in the MFC Challenge. Conversely, groups with members with individual approaches to PS more evenly distributed between "scientific" and "engineering" stances (Group N and others) tended to do better, producing MFCs with higher performance metrics. This fits with the widely held view that group heterogeneity is important in cooperative and collaborative learning [50,51]. In addition, it is the *positive interdependence* among diverse group members that is the key to the success of the group as a whole and of its individual members [52]. Positive interdependence is where group members believe that working together collaboratively or cooperatively provides greater rewards or better outcomes for themselves and hence do so. In the context of the MFC curriculum, this suggests why groups with an even mix of students with "scientific" and "engineering" approaches to PS appear to fare better overall, and especially so if the group dynamic is positive and mutually supportive.

Success in problem-solving the multiple, complex, cross-disciplinary, and ill-structured tasks in this activity could perhaps also be simply dependent upon student groups bringing a variety of *skills* to bear on the problem. Single domain skillsets may only successfully solve the problems from that domain. Group heterogeneity in PS approach (and hence heterogeneity in preferred skillset for PS) alone may go some way in affecting success. Imagine if Group G's well-crafted prototypes were filled with Group E's systematically elucidated choices of reagents and conditions! Nonetheless, it should also be obvious that the MFC curriculum engages students in collaborative group work reminiscent of real-world, project-based workplace endeavors, and this affords rich opportunities for students to develop other transferable skills such as communication and working with others. Students also have the opportunity to experience success in such complex tasks that they would unlikely otherwise be able to on their own. However, as some cases demonstrated, careful grouping of students may be important to capitalize on this overall effect. Nonetheless, the MFC program affords students of different dispositions, with different conceptual and epistemic approaches to PS, and with varied overall abilities and the opportunity to apply their knowledge and skills to complex, ill-structured tasks, and thus has the potential to develop their scientific and engineering literacies.

4.4. Significance and Impact

It should be noted that the individual and overall performance of the students in the MFC curriculum had surpassed the expectations of their teachers and the research team. Middle-school level students were able to work collaboratively to design and make functional improvised MFCs that outperformed reference kit MFCs. This unfamiliar, complex, and ill-structured set of tasks required systematic investigation and deliberate evidence-based decision-making. This suggests that, with appropriate curriculum design and scaffolding, even complex STEM activities can be successfully implemented at this level. While there was no control group for a direct comparison, the informal subjective comparisons within the cohort and the surprising exceeding of expectations suggest to us that the MFC curriculum had indeed enabled the development of aspects of scientific and engineering literacies among the learners in this study. The school subsequently continued to conduct the MFC program annually. Teachers from several other schools have also expressed interest in the program, with one other school implementing a slightly modified MFC program at both Grade 8 and Grade 10 levels. At several schools, teachers were keen to implement the program and undertook the professional development and planning to do so; however, for various reasons, were ultimately unable to proceed.

5. Conclusions

The MFC curriculum is one of very few educational activities that combine the three natural sciences and engineering while providing authentic real-life contexts in alternative energy and sustainability issues. Unlike most DBI activities such as those in Table 2, where physical sciences and engineering tasks overwhelmingly predominate, the inclusion of biological and chemical subject matter, and their integration in the core of the MFC curriculum, is quite unique. This affords an intrinsically integrative approach to STEM learning. It is thus a successful proof of concept for integrated STEM for Singapore schools, which are only just opening up to such integrative programs. Furthermore, what might generally be considered to be material for undergraduate level learning has been redesigned and adapted for learners as young as Grade 8. This is an appropriate age to appreciate the science concepts and where students are also mature and skilled enough to design workable engineering products through DBI. On the other hand, aspects of the MFC curriculum have also been trialed with older students (Grade 10 and undergraduates) and even adult learners (especially as professional development and training for teachers involved in its implementation), and they appear to find it as engaging and challenging as the students in this study. Indeed, these other groups were better able to appreciate and articulate how novel and intellectually stimulating they found the MFC curriculum activities to be. Hence, we feel that the MFC curriculum has strong potential for use across a broad range of grade and ability levels.

Author Contributions: Conceptualization, T.T.M.T.; methodology, T.T.M.T. and Y.-J.L.; formal analysis, T.T.M.T. and Y.-J.L.; investigation, T.T.M.T. and Y.-J.L.; resources, T.T.M.T.; data curation, T.T.M.T.; writing—original draft preparation, T.T.M.T. and Y.-J.L.; writing—review and editing, Y.-J.L.; visualization, T.T.M.T.; supervision, Y.-J.L.; project administration, T.T.M.T. and Y.-J.L.; funding acquisition, Y.-J.L. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the partial funding of this project from a research grant (OER 1/12 LYJ) from the Office of Education Research, National Institute of Education, Nanyang Technological University, Singapore.

Institutional Review Board Statement: Institutional Review Board ethics approval IRB-2014-11-019 was granted on 3 March 2015 to conduct the research described.

Informed Consent Statement: Informed consent was obtained from all participants and participation was fully voluntary, without compensation.

Data Availability Statement: All data collected has been treated in accordance with institutional data confidentiality and data archiving requirements and remains the intellectual property of the National Institute of Education, Nanyang Technological University, Singapore. No provision has been made for data sharing.

Acknowledgments: The curriculum package was co-developed in collaboration with teachers from the school where this study was conducted: Lisa, Boon Hwee, Khadijah, Kah Ooi, Rachel, Shi Hui, and Esther; The authors also wish to thank colleagues, Peter Lee and Choon Kook Sam for sharing of expertise and feedback; and, for the technical and administrative support from Shien Chue, Denise Tan, Rebecca Ho, Li Lian Lee, and others.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Key Parameters for Experimentation with the MFC

Two-chamber mediator-based MFCs are just one general class among many types of MFCs. There are discrete components and types of reagents that constitute such MFCs, and each of these can be relatively easily substituted and/or varied in some way on an experimental basis, and such variation may alter some performance characteristic of the MFC's electrical output. A small MFC in this type of design was developed for teaching purposes [8–10] and is commercially available in kit form from the National Centre for Biotechnology Education (NCBE), University of Reading, United Kingdom. We will refer to these as Bennetto MFCs.

Other forms of MFCs may be more prevalent in research, such as mediator-less, single-chamber MFCs, and, for educational purposes, there are soil-based MFC kits packaged for STEM learning such as the *MudWatt* from Magical Microbes [53]. However, these lack the breadth of affordances Bennetto MFCs provide for experimentation, as well as the flexibility of design choices in constructing improvised MFCs. The Bennetto MFC in NCBE kit form provides a standardized platform with which to conduct controlled experiments, with the general aim of determining optimal parameters for peak electrical output. The standard protocol, with the suggested type and concentration of reagents to be used with the NCBE kit, typically produce a voltage of about 0.5 volts. This can be used as a baseline reference MFC. Power output is generally limited to brief bursts of a few microwatts and sustained output in the range of nanowatts. Nonetheless, several such MFCs in series may be able to light up low-power LEDs or digital circuits (digital clock).

In the Experimentation phase of the MFC curriculum, students are provided with Bennetto MFCs with the standard set of reagents and protocol [9] with modifications. The key difference is the use of potassium manganate (VII) ($KMnO_4$, potassium permanganate) as the oxidizing agent used as the catholyte in the cathode chamber. $KMnO_4$ is generally safer for school use as it is a common antiseptic, whereas the reagent suggested in the standard protocol is potassium hexacyanoferrate (III), which is mildly toxic. An additional benefit of this change is an approximately 0.2 V increase in voltage over the reference cell, due to the greater difference in electronegativity between the chambers. This is an example of how changing one of the MFC's components can result in a change in its electrical output. Other such parameters that have been successfully tested are listed in Table A1. Note that not all parameters necessarily result in improved MFC performance. However, by providing some of these reagents or materials for experimentation, students will have to empirically determine the effect parameter has. Students in the MFC curriculum are usually not given the full list, with the intention of allowing for inquiry-driven and discovery-based elucidation of characteristics. Parameters for experimentation is typically distributed among the different student groups, with data shared in a common pool.

For the purposes of experimentation, measuring the voltage of the MFC over time, either open-circuit or with a relatively high resistance load to keep current draw to a minimum, serves as a simple measure of the effect of any changes made, as compared to the reference Bennetto MFC. The use of voltage sensors connected to a datalogger device is strongly encouraged. Tracking the voltage output curve over time is informative. The voltage profile over time is often characteristic of particular reagents used, and this temporal data represents a particular affordance not typical of most school science practical work, where end-point or spot measurements predominate.

Table A1. Properties of Microbial Fuel Cells for Inquiry Experimentation.

Property or Component	Parameters for Experimental Investigation and Design Decisions
Scientific Parameters [1]	
Microorganism (Species, source and quantity)	Yeast (various types of food-grade yeast) Algae (photosynthetic MFC) Bacteria (not ideal for school use) (for yeast, typically 0.05 g dried yeast per milliliter)
Food source (Type and Concentration)	Sugars: e.g., monosaccharides (glucose, fructose), disaccharides (maltose, sucrose) Other sources of food suitable for microorganism used, including mixtures (typically, ~0.3 M final concentration)
Electron mediator (Type and Concentration)	Laboratory stains and indicators: e.g., methylene blue, neutral red, phenol red, orange G, xylene cyanol, etc. Food dyes from natural extracts: anthocyanin dyes from red cabbage, butterfly pea flowers, etc. (typically, ~0.003 M final concentration and in 10-fold serial dilutions thereof)
Oxidizing agent (Type and Concentration)	Potassium hexacyanoferrate (III) Potassium manganate (VII) (typically, 0.02 M final concentration)
Temperature	Typically, room temperature, but may be varied using water-baths or incubator ovens

Table A1. *Cont.*

Property or Component	Parameters for Experimental Investigation and Design Decisions
pH	Typically, pH 7.0. All MFC reagents are prepared in phosphate buffer solution balanced to pH 7.0. Different pH may be selected, but all reagents need to be prepared in buffer solution of that pH
Engineering Design Parameters [2]	
Size and Layout of MFC	Overall size and form affects chamber volumes, surface areas of electrodes and proton-exchange membrane, and how non-motile microorganisms may settle within chamber, affecting their access to food, oxygen, electron mediator, etc.
Size and Type of Electrodes	Carbon fiber sheets, graphite rods/plates, or inert metals (gold, platinum) Carbon fiber has potential for high surface area, but tends to have lower conductivity than graphite rods (students can test for conductivity using a digital multimeter)
Chamber separation	Kit MFC uses bespoke proton-exchange membrane sandwiched between protective porous carrier films. Alternative materials: dialysis tubing/membrane or cellophane (these semi-permeable membranes lack specificity for cation-only exchange and hence allow electrons through, resulting in a slightly lower voltage). Alternative approach: salt-bridge for ion-exchange, e.g., paper strip soaked in conductive salt solution or tubing containing salt solution in agar gel
Anoxia	Limiting the microorganism's access to oxygen should allow more reducing power (electrons) to be captured by the electron mediator. Closed chamber designs with limited air space and only a small opening for loading or escape of carbon dioxide should help. Possibility of using oil layered on top of anolyte solution
Practical Design Considerations	Chamber that are easy to fill and/or have access to replace electrodes and reagents Watertight and leak-resistant design and construction methods Robust and durable for easy handling Ease of construction Availability and cost (e.g., resource limitations imposed)

[1] Scientific parameters are those that can be manipulated during the inquiry-driven experimental investigations, typically using the Bennetto kit MFCs under controlled conditions, but it is also possible to modify these during the DBI phase as students chase performance improvements. [2] Engineering design parameters are those that students typically only encounter during the DBI phase, when designing and constructing their prototypes, however these also feature opportunities for reasoning with scientific rationale.

Some parameters have greater effect on voltage output than others. Some changes may not apparently have any effect on voltage levels, but may affect other performance characteristics. For example, varying the concentration of oxidizing agent does not have a significant effect for short-term experiments; however, effects can be seen over several hours. As the oxidizing agent is consumed over time, lower concentrations limit the longevity of the MFC. Others parameters sometimes have peculiar correlations with MFC performance. For example, the voltage varies with the different concentrations of the electron mediator in a non-linear and complex way. This challenges students to make sense of the data they collect.

References

1. Kloser, M.; Wilsey, M.; Twohy, K.E.; Immonen, A.D.; Navotas, A.C. "We do STEM": Unsettled conceptions of STEM education in middle school S. T. E. M. classrooms. *Sch. Sci. Math.* **2018**, *118*, 335–347. [CrossRef]
2. Martín-Páez, T.; Aguilera, D.; Perales-Palacios, F.J.; Vílchez-González, J.M. What are we talking about when we talk about STEM education? A review of literature. *Sci. Educ.* **2019**, *103*, 799–822. [CrossRef]
3. McComas, W.F.; Burgin, S.R. A Critique of "STEM" Education. *Sci. Educ.* **2020**, *29*, 805–829. [CrossRef]
4. Ong, Y.S.; Lee, Y.-J. What does STEM education offer and how is it relevant? A content analysis of secondary school websites in Singapore. In *Concepts and Practices of STEM Education in Asia–Teachers, Teaching and Student Learning*; Cheng, M.H.M., Jones, A., Buntting, C., Eds.; Springer: Berlin/Heidelberg, Germany, *in press*.
5. Ministry of Education [MOE]. Applied Learning Programme (ALP). 2021. Available online: https://www.moe.gov.sg/secondary/courses/express/electives/?term=Applied%20Learning%20Programme%20(ALP) (accessed on 1 June 2022).

6. Dewan, A.; Van Wie, B.; Beyenal, H.; Lewandowski, Z. The Microbial Fuel Cell as an Education Tool. *Chem. Eng. Educ.* **2010**, *44*, 157–165.
7. Yeo, J.; Chen, W.; Tan, T.T.M.; Lee, Y.-J. Innovative Science and STEM Pedagogies in Singapore. In *Singapore Math and Science Education Innovation–Beyond PISA*; Tan, O.S., Low, E.L., Tay, E.G., Yan, Y.K., Eds.; Springer Nature: Singapore, 2021; pp. 189–206.
8. Bennetto, H.P. Electricity generation by microorganisms. *BIO Technol. Educ.* **1990**, *1*, 163–168.
9. Madden, D. The microbial fuel cell: Electricity from yeast. *Sci. Sch.* **2010**, *14*, 32–35.
10. Madden, D.; Schollar, J. The microbial fuel cell–Electricity from yeast cells. *Biosci. Explain.* **2001**, *1*, 1–4.
11. Potter, M.C. Electrical effects accompanying the decomposition of organic compounds. *Proc. R. Soc.* **1912**, *84*, 260–276.
12. Lovley, D.R.; Nevin, K.P. Electricity production with electrigens. In *Bioenergy*; Wall, J.D., Harwood, C.S., Demain, A., Eds.; ASM Press: Washington, DC, USA, 2008.
13. Rahimnejad, M.; Adhami, A.; Darvari, S.; Zirepour, A.; Oh, S.-E. Microbial fuel cell as new technology for bioelectricity generation: A review. *Alex. Eng. J.* **2015**, *54*, 745–756. [CrossRef]
14. Tweed, K. Fuel cell treats wastewater and harvests energy. In *Scientific American*; Springer Nature: New York, NY, USA, 2012. Available online: https://www.scientificamerican.com/article/microbial-fuel-cell-treats-wastewater-harvests-energy/ (accessed on 1 June 2022).
15. Parkash, A. Microbial Fuel Cells: A Source of Bioenergy. *J. Microb. Biochem. Technol.* **2016**, *8*, 247–255. [CrossRef]
16. Santoro, C.; Arbizzani, C.; Erable, B.; Ieropoulos, I. Microbial fuel cells: From fundamentals to applications. A review. *J. Power Sources* **2017**, *356*, 225–244. [CrossRef] [PubMed]
17. Ieropoulos, I.; Greenman, J.; Melhuish, C. Urine utilisation by Microbial Fuel Cells; energy fuel for the future. *Phys. Chem. Chem. Phys.* **2012**, *14*, 94–98. [CrossRef] [PubMed]
18. Messer, A.E. Tiny Power Generator Runs on Spit. 3 April 2014. Available online: http://news.psu.edu/story/310362/2014/04/03/research/tiny-power-generator-runs-spit (accessed on 1 June 2022).
19. Cinquin, P.; Gondran, C.; Giroud, F.; Mazabrard, S.; Pellissier, A.; Boucher, F.; Alcaraz, J.-P.; Gorgy, K.; Lenouvel, F.; Mathé, S.; et al. A glucose biofuel cell Implanted in rats. *PLoS ONE* **2010**, *5*, e10476. [CrossRef]
20. Halámková, L.; Halámek, J.; Bocharova, V.; Szczupak, A.; Alfonta, L.; Katz, E. Implanted biofuel cell operating in a living snail. *J. Am. Chem. Soc.* **2012**, *134*, 5040–5043. [CrossRef] [PubMed]
21. Nitisoravut, R.; Regmi, R. Plant microbial fuel cells: A promising Biosystems engineering. *Renew. Sustain. Energy Rev.* **2017**, *76*, 81–89. [CrossRef]
22. National Science Teachers Association [NSTA]. *Science by Design . . . Construct A Boat, Catapult, Glove, and Greenhouse/Developed by TERC*; NSTA Press: Arlington, VA, USA, 2013.
23. Fortus, D.; Dershimer, R.C.; Krajcik, J.; Marx, R.W.; Mamlok-Naaman, R. Design-based science and student learning. *J. Res. Sci. Teach.* **2004**, *41*, 1081–1110. [CrossRef]
24. Kolodner, J.L.; Camp, P.J.; Crismond, D.; Fasse, B.; Gray, J.; Holbrook, J.; Puntambekar, S.; Ryan, M. Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting Learning by Design™ into practice. *J. Learn. Sci.* **2003**, *12*, 495–547. [CrossRef]
25. Kolodner, J.L. Facilitating the Learning of Design Practices: Lessons Learned from an Inquiry into Science Education. 2002. Available online: http://scholar.lib.vt.edu/ejournals/JITE/v39n3/kolodner.html (accessed on 1 June 2022).
26. Newstetter, W.C. Guest editor's introduction. *J. Learn. Sci.* **2000**, *9*, 243–246. [CrossRef]
27. Roth, W.-M. Learning science through technological design. *J. Res. Sci. Teach.* **2001**, *38*, 768–790. [CrossRef]
28. Chue, S.; Lee, Y.-J. The Proof of the Pudding?: A Case Study of an "At-Risk" Design-Based Inquiry Science Curriculum. *Res. Sci. Educ.* **2013**, *43*, 2431–2454. [CrossRef]
29. Barron, B.; Darling-Hammond, L.; Pearson, P.D.; Schoenfeld, A.H.; Stage, E.K.; Zimmerman, T.D.; Cervetti, G.N.; Tilson, J.L.; Chen, M. How can we teach for meaningful learning? In *Powerful Learning: What We Know About Teaching for Understanding*; Jossey-Bass: San Francisco, CA, USA, 2008; pp. 11–70.
30. Hmelo, C.E.; Holton, D.L.; Kolodner, J.L. Designing to Learn About Complex Systems. *J. Learn. Sci.* **2000**, *9*, 247–298. [CrossRef]
31. Katehi, L.; Pearson, G.; Feder, M. *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*; NAP Press: Washington, DC, USA, 2000.
32. Sherin, B.L.; Edelson, D.; Brown, M. On the content of task-structured curricula. In *Scientific Inquiry and Nature of Science: Implications for Teaching, Learning, and Teacher Education*; Flick, L.B., Lederman, N.G., Eds.; Kluwer: Dordrecht, The Netherlands, 2004; pp. 221–248.
33. Schauble, L.; Klopfer, L.E.; Raghavan, K. Students' transition from an engineering model to a science model of experimentation. *J. Res. Sci. Teach.* **1991**, *28*, 859–882. [CrossRef]
34. Kolodner, J.L.; Gray, J. Understanding the affordances of ritualized activity structures for project-based classrooms. In Proceedings of the International Conference of the Learning Sciences, Seattle, WA, USA, 23–26 October 2002.
35. Schunn, C.D. How kids learn engineering: The cognitive science perspective. *Bridge* **2009**, *39*, 32–37.
36. Reeve, J.; Deci, E.L. Elements of the competitive situation that affect intrinsic motivation. *Personal. Soc. Psychol. Bull.* **1996**, *22*, 24–33. [CrossRef]
37. Tauer, J.M.; Harackiewicz, J.M. The effects of cooperation and competition on intrinsic motivation and performance. *J. Personal. Soc. Psychol.* **2004**, *86*, 849–861. [CrossRef] [PubMed]

38. Venville, G.; Rennie, L.J.; Wallace, J. Curriculum Integration: Challenging the assumption of school science as powerful knowledge. In *Second International Handbook of Science Education*; Fraser, B.J., Tobin, K., McRobbie, C., Eds.; Springer: Dordrecht, The Netherlands, 2012; Volume 24, pp. 737–750.
39. Wendell, K.B.; Rogers, C. Engineering design-based science, science content performance, and science attitudes in elementary school. *J. Eng. Educ.* **2013**, *102*, 513–540. [CrossRef]
40. Marulcu, I.; Barnett, M. Impact of an engineering design-based curriculum compared to an inquiry-based curriculum on fifth graders' content learning of simple machines. *Res. Sci. Technol. Educ.* **2015**, *34*, 85–104. [CrossRef]
41. Klahr, D.; Dunbar, K. Dual space search during scientific reasoning. *Cogn. Sci.* **1988**, *12*, 1–48. [CrossRef]
42. Apedoe, X.S.; Schunn, C.D. Strategies for success: Uncovering what makes students successful in design and learning. *Instr. Sci.* **2013**, *41*, 773–791. [CrossRef]
43. Barton, A.C.; Tan, E.; Rivet, A. Creating hybrid spaces for engaging school science among urban middle school girls. *Am. Educ. Res. J.* **2008**, *45*, 68–103. [CrossRef]
44. Van Maanen, J. *Tales of the Field: On Writing Ethnography*; University of Chicago Press: Chicago, IL, USA, 1988.
45. Ely, M.; Vinz, R.; Downing, M.; Anzul, M. On Writing Qualitative Research: Living by Words. Routledge/Falmer: London, UK, 1997.
46. Maxwell, J. *Qualitative Research Design: An Interactive Approach*; Sage Publications: Thousand Oaks, CA, USA, 1996.
47. Tan, T.T.M.; Lee, Y.-J.; Lee, P.F.P. A taxonomy for examining epistemic problem-solving approaches in STEM inquiry activities [Paper presentation]. In Proceedings of the European Science Education Research Association (ESERA) Conference, Bologna, Italy, 26–30 August 2019.
48. Li, Y.; Huang, Z.; Jiang, M.; Chang, T.-W. The effect on pupils' science performance and problem-solving ability through LEGO: An engineering design-based modeling approach. *Educ. Technol. Soc.* **2016**, *19*, 143–156.
49. Shanta, S.; Wells, J.G. T/E design based learning: Assessing student critical thinking and problem solving abilities. *International J. Technol. Des. Educ.* **2020**, *32*, 267–285. [CrossRef]
50. Webb, N.M. Peer interaction and learning in small cooperative groups. *J. Educ. Psychol.* **1982**, *74*, 642–655. [CrossRef]
51. Cheng, R.W.; Lam, S.F.; Chan, J.C. When high achievers and low achievers work in the same group: The roles of group heterogeneity and processes in project-based learning. *Br. J. Educ. Psychol.* **2008**, *78*, 205–221. [CrossRef]
52. Laal, M. Positive interdependence in collaborative learning. *Procedia-Soc. Behav. Sci.* **2013**, *93*, 1433–1437. [CrossRef]
53. Magical Microbes. Educator Resources. Available online: https://www.magicalmicrobes.com/pages/educator-resources (accessed on 1 June 2022).

education sciences

MDPI

Article

The Digital Girls Response to Pandemic: Impacts of in Presence and Online Extracurricular Activities on Girls Future Academic Choices

Francesco Faenza [1], Claudia Canali [2], Michele Colajanni [3] and Antonella Carbonaro [3,*]

[1] Department of Economics Marco Biagi, University of Modena and Reggio Emilia, 41121 Modena, Italy; francesco.faenza@unimore.it
[2] Department of Engineering Enzo Ferrari, University of Modena and Reggio Emilia, 41121 Modena, Italy; claudia.canali@unimore.it
[3] Department of Computer Science and Engineering, University of Bologna, 40126 Bologna, Italy; michele.colajanni@unibo.it
* Correspondence: antonella.carbonaro@unibo.it

Abstract: In the last few years, several initiatives based on extracurricular activities have been organized in many countries around the world, with the aim to reduce the digital gender gap in STEM (Science, Technology, Engineering, Math) fields. Among them, the Digital Girls summer camp, organized every year since 2014 by two Italian universities with the aim to attract female students to ICT (Information and Communication Technologies) disciplines, represents quite a unique initiative for its characteristics of long-duration (3–4 entire weeks) and complete gratuitousness for the participants. The COVID-19 emergency imposed severe changes to such activities, that had to be modified and carried out in the online mode as a consequence of social distancing. However, on one hand, the general lack of high-quality evaluations of these initiatives hinders the possibility to understand the actual impact of extracurricular activities on the future academic choices of the participants. On the other hand, the availability of data collected over different editions of Digital Girls has allowed us to analyze the summer camp impact and to evaluate the pros and cons of in-presence and online activities. The main contribution of this paper is twofold. First, we present an overview of existing experiences, at the national (Italian) and international levels, to increase female participation in integrated STEM and ICT fields. Second, we analyze how summer camp participation can influence girls' future academic choices, with specific attention to ICT-related disciplines. In particular, the collection of a significant amount of data through anonymous surveys conducted before and after the camp activities over the two editions allowed us to evidence the different impacts of in-presence and online extracurricular activities.

Keywords: gender gap; ICT education; human capital; extracurricular STEM activities; in-presence and online education

Citation: Faenza, F.; Canali, C.; Colajanni, M.; Carbonaro, A. The Digital Girls Response to Pandemic: Impacts of in Presence and Online Extracurricular Activities on Girls Future Academic Choices. *Educ. Sci.* **2021**, *11*, 715. https://doi.org/10.3390/educsci11110715

Academic Editors: Andrea Burrows and Mike Borowczak

Received: 14 September 2021
Accepted: 2 November 2021
Published: 8 November 2021

1. Introduction

Developing relevant digital competencies and skills for the digital transformation is vital for Europe, to fully embrace the benefits of the digital revolution and remain competitive in the global market. In the future, indeed, nearly all jobs will require digital skills, but the European Commission figures show that two-fifths of the EU workforce have little or no digital skills [1]. The lack of digital competencies becomes even more evident if we consider the gender dimension. For example, in Italy, female ICT (Information and Communication Technologies) specialists comprise 1% of all female employees (slightly below the EU average of 1.4%) [2]. The underrepresentation of women in ICT professions begins at the university; according to Eurostat 2018 data [3], about 1.3 million people in Europe are enrolled in ICT courses (in different levels of education), but only 16.7% of those who are enrolled are women (13% in Italy). On average, in Europe, men graduate 5–7 times more frequently than women in ICT [4].

To counteract these trends, a plethora of initiatives and activities for teaching youngsters integrated STEM, ICT and other technology-related disciplines have been organized in the last few years in many countries around the world. However, the study in [5] points out the lack of data about the actual impact of all these summer camps. Such activities are usually carried out by practitioners and researchers without conducting high-quality evaluations of such programs, limiting the data collection to the number of participants and to a final questionnaire about the overall satisfaction. This situation hinders the possibility to understand whether these camps actually help to attract more women into STEM and ICT careers. There is also no data available to help understand which kind of approach or activity is more effective for achieving positive outcomes.

Among the existing initiatives, a particularly significant and innovative experience is represented by the summer camp 'Digital Girls'. The Digital Girls summer camp is organized every year by two Italian universities to attract high school female students to integrated STEM disciplines and reduce the digital gender gap. The proposed real-life application of STEM is naturally integrated, meaning that STEM is the purposeful integration of the various disciplines as used in solving real-world problems [6]. Offered completely free for the participants, since 2014 the summer camp has provided girls with a learning experience, based on a team-working and learn-by-doing approach, about coding applied to creative and innovative fields, such as video game programming or Arduino-controlled robot making, and with an exposure to inspiring female role models from academia and industry. The summer camp is dedicated to students of the third and fourth grades of the high schools and no previous competencies are required in terms of coding or ICT skills. During the camp, which lasts four entire weeks, girls learn coding as applied to creative and innovative fields, such as video game programming or Arduino-controlled robot making and are exposed to inspiring female role models from academia and industry. In 2020, the COVID-19 pandemic and the consequent social distancing measures hindered the possibility to carry out the Digital Girls summer camp in presence: the 2020 camp was carried out completely online and changes were required in the types of activities and in terms of duration (reduced to three weeks). It is worth noting that the Digital Girls project has been recognized as a best practice to reduce the gender gap in ICT disciplines in the context of the Horizon 2020 Project EQUAL-IST "Gender Equality Plans for Information Sciences and Technology Research Institutions" [7] and of the Erasmus+ project Gender4STEM "Gender aware education and teaching".

The contribution of this paper is twofold. First, we provide an overview of existing experiences at the national (Italian) and international level that aim to increase female participation in STEM and ICT, thereby highlighting how, at the national and European level, Digital Girls represents a unique experience in its nature of being free, long-lasting and specifically dedicated to girls. At the international level, very few camps appear to have similar characteristics as most of the initiatives are hosted by a private Organisation, last more or less a week and are quite expensive for the participants.

Second, we present an analysis of the impact of the summer camp on the participants, comparing in-presence and online editions. To this end, data were collected through the submission of anonymous surveys before and after the summer camp activities. In this paper, we present an analysis of the survey results, focusing on several aspects, ranging from the participants' satisfaction to their perception about computer science in terms of awareness and appreciation. Furthermore, we show how participation in the summer camp may affect the girls' intention to continue their studies in ICT-related disciplines or in other fields.

The rest of this paper is organized as follows. Section 2 describes the theoretical framework in relation to the situation of the gender digital divide and presents an overview of the existing experiences to increase women's participation in ICT and STEM disciplines. Section 3 describes the Digital Girls Summer Camp as a best practice to counteract the gender gap in ICT, providing information on the project regarding the type of users, the type of activities carried out, the profiles of the girls involved, the methodology and the type of activities carried out. Section 4 evaluates the impact of the summer camp on the participants, highlighting differences between in-presence and online editions. Section 5 concludes the paper with some final remarks.

2. Overview of Initiatives to Promote Female Participation in STEM and ICT

The COVID-19 crisis has shown that adequate digital skills empowering citizens to access information and services are crucial for the whole population. In Italy, only 42% of people aged 16–74 years have at least basic digital skills (58% in the EU) and only 22% have above basic digital skills (33% in the EU). Furthermore, only 1% of Italian graduates are ICT graduates (the lowest in the EU).

The digital gap, in Europe as well as in Italy, becomes even more evident if we consider the gender dimension. According to an Organisation for Economic Cooperation and Development [8] analysis on the Programme for International Students Assessment PISA 2015 data about 15 years old students' expectations about their future, boys are more likely than girls to see themselves as working in ICT; on average 0.4% of girls and 4.8% of boys have the expectation to become employed as ICT professionals. According to Eurostat 2018 data [3], about 1.3 million people in Europe are enrolled in ICT courses (at different levels of education), but only 16.7% are women (13% in Italy). Moreover, a focus on tertiary education allows us to see that in 2015, amongst graduates in Europe, only 3.6% graduated in ICT, and only 19% of them were women, therefore [4] men graduate at a rate of 5–7 times more than women in ICT on average in Europe. In Italy, female ICT specialists comprise 1% of all female employees (slightly below the EU average of 1.4%) [2].

One of the main reasons for the observed gender gap appears to be related to cultural issues, including gender stereotypes in ICT fields: a phenomenon known as the "stereotype threat", meaning that gender stereotypes have negative consequences for girls' performance and interest in ICT and technological fields [9]. The problem is related to the perception of subjects of study and professions as masculine or feminine: ICT disciplines are perceived as masculine by the students, differently from many other academic disciplines and even from some STEM disciplines, such as mathematics. Another issue is represented by the lack of computer science disciplines in the Italian primary and secondary schools, the lack of knowledge regarding what computer science and ICT actually are, is likely to reinforce the stereotype about masculine disciplines among the younger generations [10]. OECD studies claim that girls' late exposure to computers can be associated with non-material barriers in the access to digital learning. These observations are confirmed by other results in the literature about gender gaps in STEM and ICT studies. Girls may show lower motivation than boys for computer science because they have fewer experiences with technology, and this negatively affects their interest and self-confidence in these fields [11]. Another important element that contributes to the digital gender gap is the lack of female role models in technological fields, which reinforces gender stereotypes. An interesting study [12] showed that role model exposure had positive effects on both STEM and non-STEM students' interest in STEM disciplines.

The European Commission suggests that this gender gap should be addressed by a set of policies that include breaking gender stereotypes by means of awareness-raising campaigns and concrete actions [9]. To prevent the observed segregation by gender in Tertiary education, these stereotypes must be addressed by means of earlier interventions in a student's life, including awareness-raising campaigns and training [13,14].

Given the well-known gender gap in the ICT and STEM fields [2,4], and the potential social and economic consequences of the phenomena [1], many international organizations have highlighted the need for countermeasures and have suggested active policies to counteract stereotypes regarding women in these fields. The monitoring of education systems and the creation of ad-hoc events are among the suggested actions.

Many initiatives to tackle the gender gap have been implemented in the recent years, and this paper aims to analyze the main actions taken in relation to ICT and STEM education. Although these kinds of initiatives are usually documented and advertised online, it may prove challenging to find reliable and complete information about all of them. Hence, the results presented in this paper represent an (possibly non-exhaustive) overview of the main initiatives realized in Italy and in other countries, which are summarized in Table 1.

Table 1. Italian STEM/ICT initiatives.

Name	City	Target Age	Hours of Activity	Cost Per Participant	Gender Quota	Organizer(s)	Last Edition
GCIB	Multiple cities	11–18	45	free	female only	MAW	2021
Django Girls	Multiple cities	no age limitation	8	free	female only	Python Foundation, Django Foundation	2021
NERD?	Multiple cities	16–19	10/20	free	female only	IBM	2021
Makers Camp	Milan	8–18	20 *	180€–240€	no	municipality, university	2018
H-Farm	Venice	5–18	30 *	499€/week	no	private	2021
Nuvola Rosa	Milan, Venice	17–24	80 *	free	female only	private, municipality	2017
Archicamp	Varese	6–14	30 *	15€	no	municipality	2019
Capriolo Factory	Florence	12–16	30 *	365€–400€	no	private	2021
Il_Laboratorio	FLorence	7–99	15–20	100€–135€	no	university	2021
STEM@IT	Pescara	7–16	20–80	225€–595€	no	private	2021
TechCamp@ POLIMI	Milan	14–19	27	700€	no	university	2021
Campus STEM	Florence	8+	15	140€	no	university	2020
ELLESSE	L'Aquila	7–16	12–24	740€–1320€	no	private	2021
Champions Camp	Andalo	8–13	25 *	550€–950€	no	private	2021
Phygital	online	5–15	30	199€	60% female	private	2021
Digitus Lab Camp	Milan	8–14	25	206€	no	private	2021
ToScienceCamp	Cuneo	12–14	*	190€–440€	no	private	2020
ROBOCAMP	Milan	10–14	12	410€	no	private	2020

* Not clear or missing information.

In order to better understand the possible typologies of initiatives, it could be useful to distinguish between awareness-raising initiatives, such as isolated workshops or seminars, and extracurricular activities. The latter categories could be further divided into activities that are distributed over a long period of time (e.g., school year) and summer camps, which are typically intensive and immersive activities that take place across quite short timeframe (few days/weeks).

In Italy, Girls Code It Better, NERD? and Django Girls are examples of extracurricular projects, that are entirely dedicated to girls, and that allow girls to experience ICT and related subjects. In most European nations as well as in the US, Canada and the UK, there are equivalent initiatives; Django girls, for example, has a widespread community across the globe (including Africa, Oceania, and Asia). These three initiatives are not classified as summer camps and significantly differ from Digital Girls. Django Girls is a non-profit Organisation and a community that empowers and helps women to organize free, one-day programming workshops for women, and does not impose age restrictions. These workshops can be classified as awareness-raising initiatives where participants learn the basics of Web development with Python and Django. Girls Code It Better (GCIB) is an extracurricular activity mainly directed at middle schools, whereby a school participating in the initiative follows a common format provided by GCIB central organization and carries out afternoon sessions for voluntary female students. The course is held by an external expert, chosen and trained by the GCIB central Organisation, supported by an internal tutor, and is distributed over the scholastic year. Finally, the NERD? (Non è Roba per Donne?) project, developed in 2013 by IBM Foundation Italy in collaboration with the University of Rome IT Department, hosts a few sessions each year, and workshops in which girls from high school can learn mobile app programming. The initiative now involves almost 16 universities throughout Italy.

The other initiatives included in Table 1 are summer camps. However, it is worth noting that the table does not include curricular activities that individual schools integrate into their study plan, such as projects funded by the Italian Ministry of Education through the PON (https://poninchiaro.istruzione.it/poninchiaro/?lang=en, accessed on 31 October 2021) (National Operational Programme) program or the Coding Girls project, an international format that consists of a series of events autonomously and locally organized by schools, leading to a final hackathon, in which usually around 100 girls participate. These initiatives certainly testify to the emerging initiatives that respond to the need to increase the skills of the young generations in the ICT sector, however, they are not included in our analysis due to their completely different nature with respect to Digital Girls.

Returning to Table 1, we observe that there are very few summer camps entirely or even partially dedicated to girls that are currently active, potentially highlighting a lack of knowledge or interest in the gender gap in STEM and ICT.

For the initiatives reported in Table 1, most of the camp organizers are private companies and associations, and very few are offered as either free or almost free. Nuvola Rosa was identified as one of the free camps for females only, but it seems to be no longer active; since no recent information is available and the hosting site is now offline, most of the information about the initiative is taken from newspaper articles and internet archives.

As we can observe from the last column of Table 1 (year of the last edition), many summer camps have been suspended or reorganized to be accessible from home due to the COVID-19 pandemic. With regard to the duration and cost per participant, the majority of the initiatives have a duration of one week with a cost ranging between 140€ and 1320€, except for those that are financed by municipalities or big tech companies.

Moving the analysis to the international level, the situation is harder to depict. In fact, while it is relatively easy to find international initiatives related to English-speaking nations, it is much harder to find initiatives of countries like France, Germany, Spain and other non-English speaking countries. Considering that many summer camps are generally oriented to girls and boys of their local communities, it is not easy to obtain information or details about them.

Table 2 reports the most prominent summer camps that have been established in other countries as indexed by Web search engines; given the abundance of worldwide initiatives oriented to STEM and ICT, only those specifically designed for girls have been included in this table, which presents the same columns considered for the Italian case.

As in the case of Italy, almost all of the camps have been reorganized for distance learning due to the COVID-19 pandemic, and by looking at the organizers, the duration of the activities and the cost, the majority of the camps are found to be hosted by a private organisation, last more or less than a week and are quite expensive for the participants.

Table 2. International STEM camps.

Name	Country/City	Target Age	Hours of Activity	Cost Per Participant	Gender Quota	Organizer(s)	Last Edition
Technovation	global	10–18	20+	free	female only	private	2021
GirlsSpark	Hong Kong	university students	24	free	female only	private	2018
Girls Who Code	USA	high school students	210	free	female only	no-profit	2021
MIT WTP-EECS	USA	high school students	120	3500$	female only	university	2021
Alexa Cafè	Hong Kong, USA	10–15	36	950$ **	female only	private	2021
Black Girls Code	USA	12–17	*	699$ **	female only	foundation	2021
Kode with Klossy	USA	13–18	72 *	free	female only	charitable organization	2021 *
SciGirls	USA	11-15	30	200$	female only	organization	2021
Summer STEM LAB	online	4–12	15/week	325$	female only	organization	2021
GSTEM	USA		5/week	4000$ **	female only	private	2021
Scientific and technical camps	France	13–15	24	*	female only	university	2021
Robotic institute	Germany	14–16	40–80	800€–1600€	female only	university	2021

* Not clear or missing information. ** Scholarships may apply.

Two specific initiatives deserve to be mentioned: Girls Who Code and Kode with Klossy. Founded by female role models, both projects have a significant number of hours of activities at 210 h and 72 h respectively and given the fact that they are free to participants, are substantially different with respect to the other listed initiatives and share more similarities with the Digital Girls camp. However, we did not find related results analyzing the effectiveness of the activities after being adapted as a consequence of the pandemic.

Initiatives within Scandinavian countries are also worth considering. Table 2 does not include any Scandinavian initiatives; however, a report by Norway Plan International [15], investigating the gender gap in technology in Sweden, Norway and Denmark, highlights that, although Scandinavian countries are better placed than other European countries with regards to gender equality policies, they are not exempt from the gap in technology, with an average share of 30–35% of female STEM graduates. The study also reported that IT camp initiatives carried out in the past years helped increase the percentage of female students admitted to the bachelor's degree in software development.

3. The Digital Girls as a Best Practice to Counteract Gender Gap in ICT

The first summer camp, Digital Girls, was designed and organized by the Department of Engineering 'Enzo Ferrari' of the University of Modena and Reggio Emilia in collaboration with the association of European Women Management and Development (EWMD) in 2014 in the city of Modena. Year after year, the summer camp experienced a continuous increase in the number of girls participating in the initiative, and in 2018 the camp was replicated in other cities of the Emilia Romagna Italian region. In particular, a camp was launched in the nearby city of Reggio Emilia followed by another in the city of Cesena, organized by the Department of Computer Science and Engineering of the University of Bologna.

All the editions of the summer camps Digital Girls [16,17] are characterised by a long duration, lasting 3 or 4 weeks and engage the participating girls in laboratory activities based on a learning-by-doing and project-based approach with a two-fold aim: (1) to smoothly and positively introduce girls to computer science and a “smart” technological world; (2) to give girls a better understanding of what ICT is and how it can be applied to innovative and multidisciplinary fields. More specifically, the activities were based on video games programming in the Python language and on Arduino-controlled robot making. In the last 2 weeks of the summer camp, girls worked in smaller teams of 6–7 girls, each one developing its own project. Besides acquiring basic coding competencies, this approach allowed girls to develop soft skills such as communication, teamwork and problem-solving. On the last day of the summer camp, an event was organized during which representatives from each team presented the developed projects. Furthermore, dedicated seminars consisting of speeches by external experts and women who have reached leadership positions because of scientific studies, were organized during the summer camps with the goal to promote existing female role models. The aim of such seminars was to expose girls to examples that disrupt the well-known social gender stereotypes and to present the concrete opportunities that ICT-related competencies may offer in terms of studies and careers at the local and national levels.

In 2020, the COVID-19 pandemic and the consequent social distancing measures led to the impossibility of holding the Digital Girls summer camp in-person. The 2020 editions were organized to be held completely online and some adaptations were required in terms of their duration and the available activities. A three weeks camp, based on a learn-by-doing approach, was realized for the online edition organized by Modena and Reggio Emilia, while the Cesena camp lasted for two weeks and mainly provided speeches and seminars on computer science topics.

The 2020, Modena-Reggio Emilia online edition was organized with three weeks of activities, including daily meetings that lasted three hours from Monday to Thursday. The girls were divided into two groups that focused on programming activities concerning the following application fields: Web sites development and game programming with Python. Even though the online nature of the summer camp theoretically facilitates the participation of a greater number of girls with respect to the past editions, the choice of a team-based approach and the consequent requirements in terms of teachers/tutors actually limited the overall participation to a total of 75 girls.

The 2020, the Cesena online edition was organized with daily meetings of 2 h on different topics of computer science. The different topics were explored by inviting female and male speakers. Speeches were organized on the following topics: open source software, informatics and 3D cell cultures, quantum computing, the problem-solving approach as a key element of professionalism, biometrics and computer science in primary schools. The seminary-based approach allowed a greater number of girls to participate in the activities.

From the comparison with the initiatives described in Section 2, we can state that the summer camp Digital Girls is an innovative project, and both its duration and the fact that it is free for the participants make this initiative unique.

4. Impact Evaluation

In this section, we present the impact evaluation carried out on the data collected over the 2019 and 2020 editions of the summer camp. In the rest of this section, we first present the methodology followed for the data collection and analysis. Then, we describe the obtained results, analyzing the impacts under several points of view, and we conclude with a final discussion.

4.1. Materials and Methods

During each edition of the summer camp, we collected data from the participants by submitting two surveys, one before and one after the camp. Surveys were submitted during the camp’s hours in the form of anonymous online forms. The questionnaire submitted before the camp (hereafter *before camp questionnaire*) consists of 30 questions that can be divided into three main categories, which are personal background, personal choices (including questions related to future choices in terms of studies and career) and computer science perception. Questions can be further classified based on the typology of answers, such as long and short free-text, numerical input, single-choice, multiple-choice and Likert scale choice. The same categorization and typology of questions appear in the questionnaire submitted at the end of the camp activities (hereafter *after camp questionnaire*); some questions are repeated to evaluate the change in the girls' answers, and additional questions, specific to camp satisfaction and impact, were included, for a total of 35 questions.

The analysis sought to develop an understanding of whether different editions of the summer camp (in-presence vs online, learn-by-doing vs seminary-based experience) may have different impacts on the participating girls. To this aim, our evaluation considers the last two years of the summer camp: the 2019 in-person edition, with 107 participants at the camp in Modena-Reggio Emilia (hereafter MO-RE) and 50 in Cesena (all editions based on a learn-by-doing approach) and the 2020 online edition, with 75 girls in MO-RE (learn-by-doing approach) and 160 girls in Cesena (seminary-based approach). More specifically, the analysis reported in this paper focuses on the girls' overall satisfaction, their perception about computer science in terms of awareness and appreciation, and their intentions regarding future academic/career choices. Finally, we investigate which aspects were more appreciated over the summer camp editions. The specific questions used in the survey and the methods to process the girls' answers are detailed in the following subsection.

4.2. Results

The Digital Girls summer camp **satisfaction** represents an essential aspect of the analysis. In both of the editions considered in this analysis, participants were asked to answer the question: "How do you evaluate your overall satisfaction about the camp experience?". For this question we used a Likert 5-point scale with answers ranging from 1 (very dissatisfied) to 5 (very satisfied).

In Figure 1, we report the results for the 2019 in-presence edition (left side) and for the 2020 online edition (right side). For each edition, we consider the average satisfaction expressed by the participants at each single camp (MO-RE and Cesena), which is represented through vertical bars, and the average overall satisfaction for each edition, represented with the horizontal dotted lines. While the satisfaction for MO-RE and Cesena camps are almost identical in the 2020 edition, we observe a difference in the results of the 2019 edition. The difference can be explained by the high level of experience of the MO-RE camp's teachers, as in 2019 the MO-RE camp was at its sixth edition, while the Cesena camp was only at its second edition and there was a significant turn-over among the teachers. However, we see that the overall edition averages, represented by the dotted lines, do not change significantly between the in-presence and online edition, as shown in Figure 1.

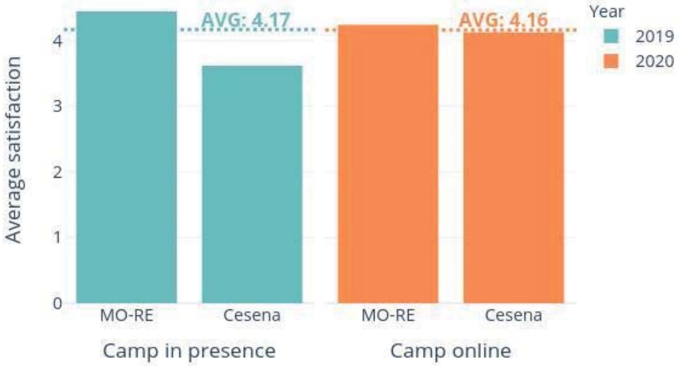


Figure 1. Average Summer Camp Satisfaction (1–5 range).

The results are quite surprising as, we expected a less enthusiastic and positive perception of the online edition of the summer camps due to the long period of online lessons and social distancing caused by the COVID-19 pandemic. Moreover, both the MO-RE and Cesena online camps in 2020 obtained high satisfaction levels, meaning that girls appreciated both a learn-by-doing teamwork experience and a seminary-based approach.

We now focus our evaluation on one of the camp's main objectives, that is, to increase awareness and improve perception about ICT and computer science (CS) disciplines. Two specific questions were included in the survey to this end, one regarding **CS awareness**, aimed at understanding whether the participants acquired a more precise idea of what CS is; the other on **CS appreciation**, investigating whether the personal perception of CS improved after attending the summer camp.

For CS awareness, we asked girls: "How much did you clear your mind about computer science?" with the possibility to answer with: "Not at all", "Slightly", "Moderately", "Very", "Extremely"; for the aspect of CS appreciation we asked: "What is your idea about computer science after the camp?" giving as possible answers: "I like it much less than before", "I like it less than before", "Unchanged", "I like it more than before", "I like it much more than before". For both answers, we converted the choice to a Likert 5-point scale. The results show an average rating of 3.79 (out of 5) points for CS awareness and 4.02 (out of 5) points for CS appreciation, with no significant differences between in-presence vs online editions, or between online learn-by-doing vs a seminary-based approach.

As already stated, the awareness objective is strictly related to the general aim to introduce girls to computer science to help them make a more informed choice about their future studies and to hopefully reduce the gender gap in ICT fields. The approach used to design the summer camp activities encourages practice and interaction by focusing on individual learning and experimentation, with the specific aim to attract girls to computer science. To evaluate such a critical impact of the camp, we tried to measure the change in the intentions about future study choices as a consequence of participation in the activities provided by Digital Girls. We included two specific questions in the surveys submitted before and after the camp: (1) "Do you intend to continue your studies at the university?", and in case of a positive answer (2) "In which field do you intend to continue your studies?". For the second question, we allow multiple choices, which we converted to the International Standard Classification of Education (ISCED) [18], including the option related to the F06 field—Information and Communication Technologies.

We first evaluated the answers provided in the *before camp questionnaire*. We obtained similar results between the 2019 and 2020 editions; hence, for reasons related to space, we report only the data about the 2019 summer camp (shown in Figure 2).

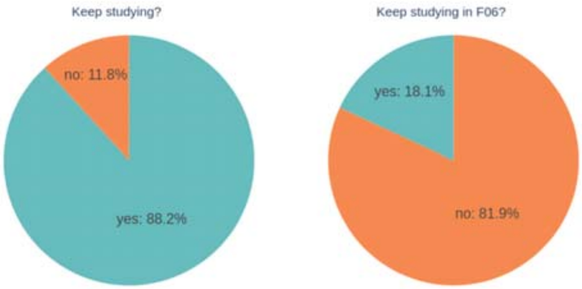


Figure 2. Future academic choices emerged before the camp.

From the left side of Figure 2, we observe that almost 88% of girls express the intention to continue their studies after high school, in any field of study, while the percentage of girls with the intention to continue in F06, that is the ICT field, is around 18% (right part of the figure). We note that this percentage is much higher than the average percentage of women enrolled in F06 studies at the European level. In fact, as shown by Eurostat data [19] on students' enrollment in tertiary education, 10.560.208 women are enrolled in tertiary education in Europe (EU28), but only 182.631 are enrolled in the ICT field (corresponding to 1.7%). Our results are very surprising, considering the European scenario, but they can be explained by the fact that the Digital Girls summer camp is likely to attract a higher percentage of girls interested in continuing their studies in ICT disciplines compared to the average of girls of the same age. Moreover, we should consider here that girls express an intention, while the Eurostat data reports the effective percentage of female students enrolled in the F06 field.

To better understand the summer camp's impact, we decided to evaluate the connection between their choice of the academic studies and their previous experience in coding, if any, which may have been acquired during their education. From the *before camp questionnaire*, we know that only 26.2% of the participants had already tried coding before attending the summer camp. Hence, we analyzed the difference in the university choices, considering the data clustered on previous coding experience. The results are shown in Figure 3.

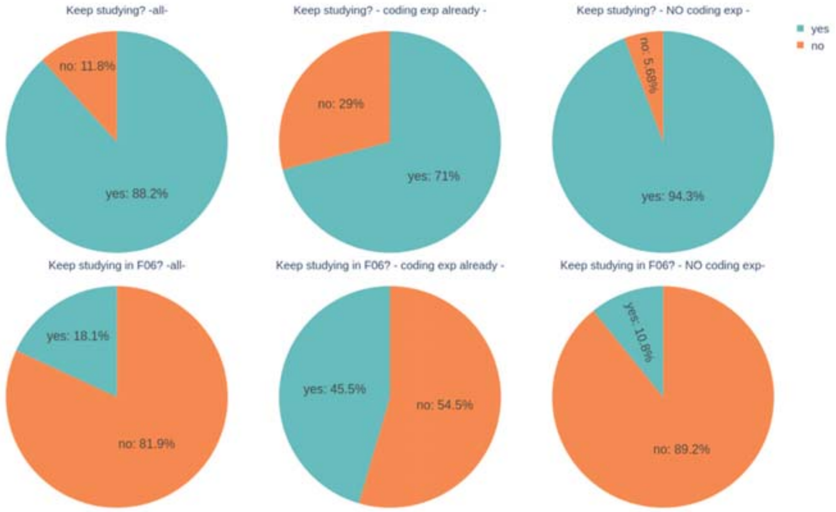


Figure 3. Future academic choices, disaggregated based on previous coding experience, as emerged before the camp.

Figure 3 outlines a significant difference between the girls who have already experienced coding and their peers without the same experience. On the one hand, a higher percentage of girls with previous coding experience express the intention of not continuing their studies: this can be explained by the fact that they are aware of having a skill, that is highly appreciated and valued in the current job market, which allows them to easily find employment. On the other hand, among the girls aiming to continue their studies, it is evident that those who have already experienced coding are much more likely to continue their studies in the F06 ICT sector than their peers (45.5% vs. 10.8%). This result is very significant as it highlights the importance of experiencing coding at school and how such an experience may positively and significantly impact students' willingness to choose F06 as a field study as a woman.

Let us now evaluate the impact of the summer camp on the girls' future choice of studying in an ICT field. To this end, we compare the girls' answers before and after the summer camp experience. Furthermore, we compare the data obtained in 2019 and 2020 to understand any potential different impacts between in-presence and online editions of Digital Girls.

Figure 4 compares the answers provided before (left part of the graph) and after (right part of the graph) the in-presence summer camp in 2019: the results show that the percentage of girls motivated to continue studies in F06 ICT fields increases from 18.1% to 25.9%. The results show that the summer camp experience carried out in-presence appears to positively affect the girls' willingness to choose a computer science discipline.

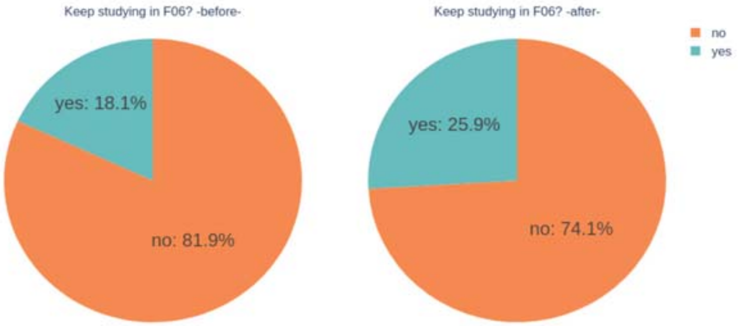


Figure 4. Data about 2019 summer camp (in-presence).

A fascinating result emerges when comparing 2019 in-presence and 2020 online results, represented in Figure 5, such that we observe a similar increment.

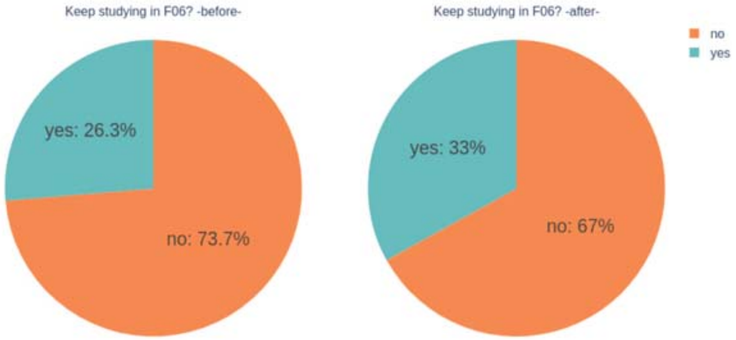


Figure 5. Data about summer camps 2020 (online).

We note a higher percentage of girls choosing an ICT field in the *before camp questionnaire* in 2020 compared to 2019. The outcome could be motivated by the higher presence of girls with previous programming experience; moreover, we suppose that the online edition of the summer camp may attract highly motivated girls. In fact, the selection of extracurricular online activities is typically broader and, the effect of joining friends in the same classroom/school to share an in-presence experience is missing. On the other hand, the percentage of girls willing to continue studying in F06 fields that emerged from the 2020 *after camp questionnaire* do not significantly differ from what we observed for the 2019 edition. The summer camp experience seems to have a positive impact on the participants' future choices, both for the in-presence and online editions.

Finally, to further investigate the difference among the camp editions, we analyze the answers to two free-text questions: (a) "describe what you liked more about the camp"; (b) "describe what you liked more about your project". Specifically, one or more significant tags were assigned to each answer to characterize it. For example, the answer "I liked to work in a team" has been tagged with the single tag "teamwork", while the answer "I liked the collaboration within my group and teacher's friendliness" has been tagged with the following tags: "teamwork" and "teaching_style". Then, the occurrences of tags were counted to identify the main trends. Figure 6 shows the percentage of the tag occurrences during the two considered editions of 2019 (in presence) and 2020 (online). A missing column for a tag means zero occurrences of that specific tag. One of the main observations is the absence of the tag "friendship" in the comments about the 2020 online edition: this tag was assigned to all comments that included the experience of getting to know someone else, which were included in the 2019 edition's comments, in statements such as "I liked to meet new people" or "I liked to interact with new people and make new friends". The absence of this tag evidences the missing social interaction among girls and the difficulty to establish relationships and new friendships during online activities.

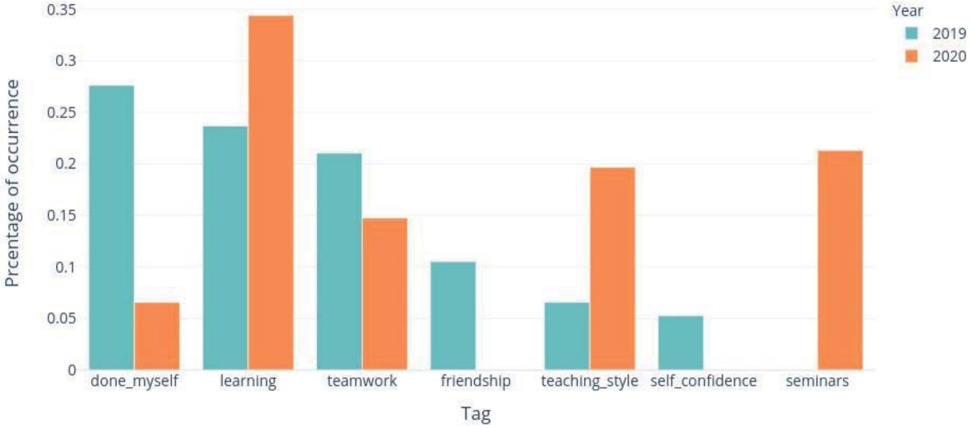


Figure 6. Tags analysis.

Moreover, we observe that the frequency of the tag "teamwork" slightly decreased for the online edition in comparison to the in-presence edition, stressing the increased difficulty of collaborating and interacting with other participants during the project development phase. We also note that the tag "seminars" is only present in the 2020 online edition: this is motivated by the fact that, when engaged in laboratory activities and in the implementation of a complex project (as in the in-presence edition), girls express less appreciation for seminars, because they feel the urge to finalize their projects.

A very interesting observation about the tag "self-confidence" emerged that is absent from the online edition: in-presence activities appear to be more effective in increasing the girls' self-confidence in computer science. The same concept emerges with the tag "done-myself", which is much more present in the results related to the in-presence edition. These observations reveal how a fundamental element to counteract the gender gap [20,21] is more likely to be achieved by means of in-presence laboratory activities. Female students are usually much less confident in their computer skills than male students. Hence, improving girls' self-confidence in ICT fields may comprise a key element to engage more women in computer science [22–25].

4.3. Discussion

If we want to strengthen girls' integrated STEM capabilities and development, we need to do so in a way that does not increase or reproduce the patterns of inequality and exclusion that our societies are trying to overcome. Generally, we require more data on the main variables influencing the digital divide, and a closer analysis of its relationship with social class, age and ethnicity [26]. However, we have a clearer picture when it comes to gender. For example, the Commission's 2018 study "Women in the Digital Age" pointed out that only 24 out of 1000 female graduates studied an ICT-related subject and only six went on to work in the digital sector [27]. However, the COVID-19 crisis has exposed a widening digital divide; over the past few months, our planet has been pushed into a compulsory 'digital metamorphosis', a true collective experiment launched without a strategy or parachute [28]. The European Commission, the European Parliament and EU leaders agreed on a recovery plan that will lead the way out of the crisis and lay the foundations for a digital, greener and more sustainable Europe [29]. This is also a time during which citizens want to bridge digital divides and accelerate digital transformation, and three out of four Europeans think that there are 3 priority areas that need to be addressed—digital public services, digital skills and broadband internet access [30]. All of these factors lead us to believe that this is the right time to act even more decisively and bring best practices to the attention of the international community for widespread dissemination and to encourage the successful implementation of an integrated STEM program [31]. Among these, the Digital Girls summer camp stands out as a unique initiative, that is starting to garner positive results, specifically in terms of concretely reducing the gender gap in ICT. At the University of Modena and Reggio Emilia, where the camp has been running since 2014, the percentage of female students enrolled in the course of Computer Engineering has increased from almost 15% in the academic year 2013/14, to over 20% in the last two years. This increase is particularly interesting if compared with the percentage of female students globally enrolled at the Department of Engineering (which includes several other courses in Engineering), for which the average share has remained at around 15% from 2014 to now.

5. Conclusions

In this paper, we described our experiences of organizing the summer camp Digital Girls. Due to the COVID-19 emergency, we have profoundly modified the 2020 edition of the summer camp, holding specific online activities as opposed to in past editions where activities were carried out in-presence. We have nevertheless maintained a well-integrated approach to provide opportunities for students to learn in more relevant and stimulating ways, to encourage the use of higher-level critical thinking skills, and to improve problem-solving skills. The results in this paper reveal an interesting comparison between the impacts of in-presence, pre-pandemic editions of the summer camp and the online version of Digital Girls formulated in response to the health emergency. This analysis can act as a valuable reference and inspiration for those who wish to replicate the effort within their communities to build the necessary parachute for the requirements of the digital transformation occurring throughout the world. In future, we plan to extend the initiative to other territories within our region through collaborations with other Universities and economic and political institutions; we believe that only the active collaboration of all stakeholders will help to redress the problem of the digital gender gap and mitigate the contextual factors that foster it.

Author Contributions: Conceptualization, A.C. and C.C.; methodology, C.C., F.F. and A.C.; software, F.F.; validation, M.C.; formal analysis, M.C.; investigation, A.C., C.C. and F.F.; data curation, F.F.; writing—original draft preparation, A.C., C.C. and F.F.; writing—review and editing, C.C. and A.C.; supervision, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Commission. ICT for Work: Digital Skills in the Workplace, Report. March 2021. Available online: https://digital-strategy.ec.europa.eu/en/library/ict-work-digital-skills-workplace (accessed on 31 October 2021).
2. European Commission. The Digital Economy and Society Index (DESI), Shaping Europe's Digital Future Report. 2020. Available online: https://ec.europa.eu/digital-single-market/en/digital-economy-and-society-index-desi (accessed on 31 October 2021).
3. Eurostat, Girls and Women under-Represented in ICT, Eurostat Report. 2018. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20180425-1 (accessed on 31 October 2021).
4. European Commission. *Women in the Digital Age*; DG Communications Networks, Content & Technology: Luxemburg, 2018.
5. Mervis, J. *They're Fun. But Can STEM Camps for Girls Really Make a Difference?* Science, American Association for the Advancement of Science: Washington, DC, USA, 2018.
6. Breiner, J.M.; Harkness, S.S.; Johnson, C.C.; Koehler, C.M. What is STEM? A discussion about conceptions of STEM in education and partnerships. *Sch. Sci. Math.* **2012**, *112*, 3–11. [CrossRef]
7. Canali, C.; Addabbo, T.; Moumtzi, V. A best practice for attracting female students to enrol in ICT studies. In Proceedings of the 2nd Int. Conference on Gender Research (ICGR), Rome, Italy, 11–12 April 2019.
8. OECD. *PISA 2015 Results (Volume I): Excellence and Equity in Education*; PISA, OECD Publishing: Paris, France, 2016. [CrossRef]
9. Régner, I.; Steele, J.R.; Ambady, N.; Thinus-Blanc, C.; Huguet, P. Our future scientists: A review of stereotype threat in girls from early elementary school to middle school. *Rev. Int. De Psychol. Soc.* **2014**, *27*, 13–51.
10. OECD. *Students, Computers and Learning: Making the Connection*; PISA, OECD Publishing: Paris, France, 2015. [CrossRef]
11. Barker, L.J.; Aspray, W. *The State of Research on Girls and IT, Women and Information Technology: Research on Underrepresentation*; Cohoon, J.M., Aspray, W., Eds.; MIT Press: Cambridge, MA, USA, 2006; pp. 3–54.
12. Shin, J.E.L.; Levy, S.R.; London, B. Effects of role model exposure on STEM and non-STEM student engagement. *J. Appl. Soc. Psychol.* **2016**, *46*, 410–427. [CrossRef]
13. OECD. PISA results in focus. In *Programme for International Students Assessment*; OECD Publishing: Paris, France, 2015.
14. Davaki, K.; European Parliament, Policy Department for Citizen's Right and Constitutional Affairs. The Underlying Causes of the Digital Gender Gap and Possible Solutions for Enhanced Digital Inclusion of Women and Girls. 2018. Available online: http://www.europarl.europa.eu/RegData/etudes/STUD/2018/604940/IPOL_STU(2018)604940_EN.pdf (accessed on 31 October 2021).
15. Talks, I.; Edvinsson, I.; Birchall, J. *Programmed Out: The Gender Gap in Technology in Scandinavia*; Plan International Norway: New York, NY, USA, 2019.
16. Faenza, F.; Canali, C.; Carbonaro, A. Evaluating different approaches to closing the gender gap at ICT summer camps in Italy. In Proceedings of the International Conference on Gender Research (ICGR), Aveiro, Portugal, 21–22 June 2021.
17. Faenza, F.; Canali, C.; Carbonaro, A. ICT Extra-Curricular Activities: The "Digital Girls" Case Study for the Development of Human Capital. In Proceedings of the International Research & Innovation Forum, Athens, Greece, 7–9 April 2021.
18. Eurostat. International Standard Classification of Education (ISCED). 2016. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_Standard_Classification_of_Education_(ISCED) (accessed on 31 October 2021).
19. Eurostat. Students Enrolled in Tertiary Education by Education Level, Programme Orientation, Sex and Field of Education, European Commission Dataset Detail. 2019. Available online: https://ec.europa.eu/eurostat/web/products-datasets/-/educ_uoe_enrt03 (accessed on 31 October 2021).
20. Pollock, L.; McCoy, K.; Carberry, S.; Hundigopal, N.; You, X. Increasing high school girls self confidence and awareness of CS through a positive summer camp experience. In Proceedings of the 35th Symposium on Computer Science Education, Norfolk, VA, USA, 3–7 March 2004.
21. Main, J.B.; Schimpf, C. The underrepresentation of women in computing fields: A synthesis of literature using a life course perspective. *IEEE Trans. Educ.* **2017**, *60*, 296–304. [CrossRef]
22. Carbonaro, A.; Ravaioli, M. Peer assessment to promote deep learning and to reduce a gender gap in the traditional introductory programming course. *J. e-Learn. Knowl. Soc.* **2017**, *13*, 121–129.
23. Carbonaro, A. Improving web search and navigation using summarization process. In *World Summit on Knowledge Society*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 131–138.
24. Murphy, A.; Kelly, B.; Bergmann, K.; Khaletskyy, K.; O'Connor, R.V.; Clarke, P.M. Examining unequal gender distribution in software engineering. In *European Conference on Software Process Improvement*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 659–671.
25. Carbonaro, A. Good practices to influence engagement and learning outcomes on a traditional introductory programming course. *Interact. Learn. Environ.* **2019**, *27*, 919–926. [CrossRef]
26. Elena-Bucea, A.; Cruz-Jesus, F.; Oliveira, T.; Coelho, P.S. Assessing the role of age, education, gender and income on the digital divide: Evidence for the European Union. *Inf. Syst. Front.* **2020**, *21*, 1–15. [CrossRef]
27. Pladaitė, M.; Pypaert, P. *Europe and North America, Agenda for Sustainable Development*. 2021. Available online: https://unstats.un.org/sdgs/report/2021/The-Sustainable-Development-Goals-Report-2021.pdf (accessed on 31 October 2021).
28. Zheng, Y.; Walsham, G. Inequality of what? An intersectional approach to digital inequality under COVID-19. *Inf. Organ.* **2021**, *31*, 100341. [CrossRef]

29. Rodríguez, P.M. 7. The Eu Budget: The New Mff and the Recovery Instrument: Next Generation Eu. 2021. Available online: https://www.ieaf.es/images/Publicaciones-FEF/Anuarioeuro2021/10_The_EU_budget.pdf (accessed on 31 October 2021).
30. Rodriguez-Hevía, L.F.; Navío-Marco, J.; Ruiz-Gómez, L.M. Citizens' involvement in E-government in the European Union: The rising importance of the digital skills. *Sustainability* **2020**, *12*, 6807. [CrossRef]
31. Kelley, T.R.; Knowles, J.G. A conceptual framework for integrated STEM education. *Int. J. STEM Educ.* **2016**, *3*, 1–11. [CrossRef]

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Education Sciences Editorial Office
E-mail: education@mdpi.com
www.mdpi.com/journal/education

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34

www.mdpi.com

ISBN 978-3-0365-5650-5