RETHINKING STEM EDUCATION

Theoretical and Sociocultural Frameworks

Editor

Mustafa Tevfik Hebebci

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Rethinking STEM Education:
Theoretical and Sociocultural Frameworks

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About the Book

This book offers a comprehensive and interdisciplinary exploration of contemporary STEM education, bringing together theoretical foundations, empirical insights, and practical applications to address the evolving demands of teaching and learning in the 21st century. Designed for researchers, graduate students, teacher educators, and practitioners, the volume examines how STEM education can be effectively conceptualised, implemented, and evaluated within diverse educational and sociocultural contexts.

The chapters collectively address core theoretical perspectives underpinning STEM education, including constructivist, radical constructivist, cognitive, and sociocultural approaches. These frameworks are linked to learner-centred pedagogical models such as inquiry-based, problem-based, experiential, and project-based learning, demonstrating how theory informs classroom practice. Special emphasis is placed on mathematics as a central and integrative STEM discipline, with in-depth discussion of students' conceptual development—particularly in relation to fractions—across different age groups.

The book also explores the transformative role of technology in STEM education, highlighting emerging tools such as artificial intelligence, robotics, simulations, and virtual learning environments. Issues of assessment, feedback, and evaluation are addressed through innovative and inclusive frameworks that move beyond traditional testing to capture higher-order, interdisciplinary competencies.

Importantly, the volume extends STEM education beyond technical proficiency by engaging with sociocultural, ethical, environmental, and community-based dimensions of learning. Chapters on scientific wealth, community engagement, responsible innovation, environmental sustainability, and culturally grounded STEAM+S frameworks emphasise equity, identity, heritage, and ethical responsibility. These perspectives collectively reframe STEM education as a means of fostering not only academic achievement, but also social awareness, cultural sustainability, and responsible citizenship.

By integrating theory, research, and practice, this book provides a coherent and forward-thinking resource for those seeking to design, implement, and evaluate STEM education in ways that are innovative, inclusive, and responsive to global and local challenges.

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Foreword

STEM education has evolved far beyond a collection of disciplinary silos into a dynamic, interdisciplinary, and socially embedded educational paradigm. In an era marked by rapid technological advancement, global uncertainty, and complex societal challenges, the need for theoretically grounded, ethically responsible, and culturally responsive STEM education has never been more urgent. This edited volume responds to that need by offering a comprehensive and forward-looking examination of STEM education through diverse theoretical, pedagogical, sociocultural, and ethical lenses.

The chapters brought together in this book reflect a shared commitment to deepening our understanding of how learners construct knowledge, develop competencies, and engage meaningfully with real-world problems. Drawing on foundational perspectives such as constructivism, radical constructivism, cognitive load theory, and sociocultural theory, the volume establishes a robust theoretical base for contemporary STEM pedagogy. These perspectives are not treated as abstract constructs; rather, they are carefully connected to learner-centred instructional models, classroom practices, assessment frameworks, and curriculum design.

A distinctive strength of this book lies in its holistic scope. Mathematics is positioned as a core integrative component of STEM, with particular attention given to conceptual learning processes such as fractions through a radical constructivist lens. Technology is examined not merely as a tool, but as a transformative force shaping learning environments, assessment practices, and ethical decision-making. Equally important, the volume foregrounds measurement, evaluation, and feedback processes, emphasising inclusive, equitable, and formative assessment models aligned with 21st-century skills.

Beyond pedagogy and technology, the book makes a significant contribution by situating STEM education within broader sociocultural, ecological, and ethical contexts. Chapters exploring scientific wealth, community engagement, responsible innovation, environmental sustainability, and culturally grounded STEAM+S frameworks challenge deficit narratives and economic reductionism. Instead, they offer expansive visions of STEM education that recognise identity, heritage, community, and ethical responsibility as integral to meaningful learning and innovation.

Collectively, this volume speaks to researchers, teacher educators, policymakers, and practitioners seeking to rethink STEM education for a rapidly changing world. It invites readers to move beyond narrow definitions of success and toward a more inclusive, reflective, and socially responsive understanding of what it means to educate future scientists, engineers, innovators, and responsible global citizens.

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CONTENTS

Chapter 1

Theoretical Foundations of STEM Education

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Chapter Highlights

This chapter examines the theoretical foundations that shape the design, implementation, and evaluation of STEM education across diverse educational contexts. Emphasising interdisciplinary approaches, it explores cognitive, constructivist, and sociocultural learning theories that underpin STEM pedagogy. By critically analysing these theories and models, the chapter provides educators and policymakers with a deeper understanding of the epistemological assumptions underpinning STEM practices. Furthermore, it examines how theoretical constructs influence the development of 21st-century competencies, including critical thinking, collaboration, and creativity. This theoretical grounding is essential for fostering inclusive and adaptive STEM learning environments that respond to diverse learners' needs. In short, the chapter:

- Delineates key theoretical foundations—constructivism, cognitive load theory, and sociocultural theory—that shape the design and implementation of effective STEM pedagogy
- Examines practical pedagogical models, including experiential, inquiry-based, and problem-based learning, which operationalise these theories into learner-centred instructional strategies.
- Bridges theoretical concepts with practical classroom implementation, using an example lesson plan on mathematical modelling in middle school mathematics.
- Explores the role of theoretical constructs and epistemology in fostering essential 21st-century competencies such as critical thinking, collaboration, and innovation.

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Introduction

Science, Technology, Engineering and Mathematics (STEM) education is increasingly recognised as an essential foundation for preparing learners to navigate rapidly evolving scientific, technological, and social landscapes. Global policy reports emphasise STEM literacy as a critical component of economic development, innovation capacity, and citizenship in the 21st century (Bybee, 2013). As countries invest in integrated STEM curricula, the theoretical and pedagogical foundations underpinning these initiatives become central to ensuring meaningful and equitable learning outcomes. Therefore, a deep exploration of the learning theories guiding STEM instructional design is crucial for both practitioners and policymakers.

Additionally, recent scholarship underscores that effective STEM education is not merely the integration of four disciplines but a transformation of learning environments through inquiry, collaboration, and problem-driven engagement (Honey et al., 2014). These environments must be grounded in cognitive and sociocultural theories that explain how students construct knowledge and interact with tools, peers, and contexts. The aim of this chapter is to bring together these theoretical perspectives and demonstrate how they shape the pedagogical models widely used in STEM implementation. By connecting theory to practice, the chapter provides a roadmap for designing coherent and impactful STEM learning experiences.

Theoretical Underpinnings of STEM Education

This section introduces three theoretical underpinnings of STEM education, as described in Figure 1: constructivism, cognitive load theory and sociocultural learning theory.

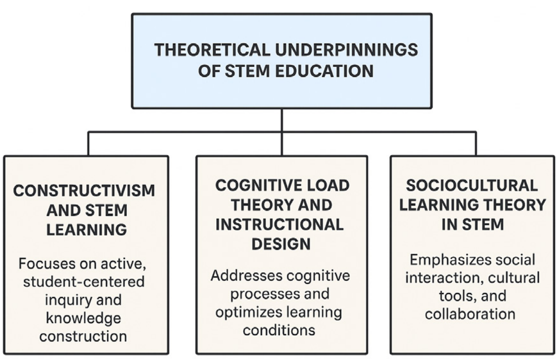

Figure 1. Theoretical underpinnings of STEM education.

Constructivism and STEM Learning

Constructivism posits that learning is an active meaning-making process in which learners integrate new information with existing cognitive structures (Piaget, 1973). Within STEM classrooms, this theoretical stance underpins approaches that prioritise experimentation, model construction, and exploration of open-ended problems. For example, engineering design tasks allow learners to iteratively test and revise their ideas, embodying the constructivist belief that understanding emerges through interaction with the environment. Such approaches align with current STEM reforms promoting student-led inquiry and real-world problem-solving.

Beyond individual cognition, social constructivism (Vygotsky, 1978) enriches STEM by emphasising collaboration, discourse, and mediated learning. Digital simulations, collaborative robotics tasks, and shared data investigations serve as cultural tools that facilitate knowledge co-construction. Research shows that when learners articulate reasoning, engage in argumentation, and negotiate solutions within teams, their conceptual understanding deepens (English, 2016). Constructivist STEM environments therefore support not only knowledge acquisition but also epistemic practices such as modelling, data interpretation, and evidence-based reasoning.

Constructivist principles also align strongly with interdisciplinary STEM approaches. When students engage with phenomena that require the integration of science concepts, mathematical reasoning, and technological tools, they develop interconnected knowledge structures rather than isolated skills (Roehrig et al., 2021). These cognitively rich experiences encourage learners to draw on multiple disciplines and generate novel solutions—a key aim of STEM education. The interdisciplinary context provides fertile ground for learners to activate prior knowledge and expand their conceptual networks through authentic engagement.

Moreover, constructivism highlights the importance of learner autonomy, intrinsic motivation, and choice, which are increasingly recognised as central to STEM motivation and identity development. Research shows that when students perceive autonomy in exploring STEM problems, they exhibit higher perseverance, creativity, and willingness to engage with challenging tasks (Kelley & Knowles, 2016). Thus, constructivist learning environments help cultivate positive STEM identities, particularly for students who may feel marginalised in traditional didactic settings.

Cognitive Load Theory and Instructional Design

Cognitive Load Theory (Sweller, 1988) offers a cognitive psychology lens on how learners process and store new information, highlighting the limited capacity of working memory. STEM subjects often present highly complex information and multi-step problem-solving tasks that can overwhelm learners' cognitive resources. Effective STEM instruction thus involves designing learning materials and tasks that optimise cognitive load by:

- Managing intrinsic load through sequencing and chunking complex content,
- Reducing extraneous load by removing unnecessary information and distractions, and
- Enhancing germane load by encouraging schema construction and automation.

Instructional strategies informed by cognitive load theory encompass the use of visualisations, worked examples, scaffolding, and guided inquiry that progressively shift responsibility to the learner. For example, teaching mathematical modelling in a middle school classroom can start with structured guided practice, gradually allowing students to independently approach complex problems. Optimising cognitive load supports knowledge retention, transfer, and problem-solving abilities vital in STEM.

Furthermore, CLT offers valuable implications for technology-enhanced STEM learning. While digital tools such as simulations, dynamic geometry environments, and data visualisation platforms can enhance learning, they may also introduce unnecessary complexity. Effective STEM instructional design must therefore ensure that technology serves as a cognitive amplifier rather than a distraction (Honey et al., 2014). For example, simulations that allow learners to manipulate a single variable at a time help manage intrinsic load, whereas overly complex interfaces may introduce extraneous load and hinder conceptual understanding.

Recent research highlights the importance of aligning CLT with interdisciplinary STEM tasks. Integrated tasks often require learners to synthesise concepts from multiple domains, increasing intrinsic load. Teachers can manage this by explicitly modelling interdisciplinary thinking, using visual maps, or chunking tasks into disciplinary subcomponents before integration (Sanders, 2009). Such strategies allow learners to navigate complexity while still benefiting from the richness of integrative STEM problem-solving.

Sociocultural Learning Theory in STEM

Sociocultural theory situates learning within interpersonal, cultural, and historical contexts, advocating that cognitive development is inseparable from social interaction and cultural mediation (Vygotsky, 1978). Within STEM classrooms, this translates to fostering collaborative learning communities where dialogue, peer mentoring, and interaction with cultural artefacts (e.g., digital tools, scientific instruments) mediate understanding. Culturally responsive teaching practices rooted in this theory ensure that STEM education honours diverse backgrounds and experiences, enhancing engagement and equitable participation. Collaborative technologies, such as virtual labs and coding platforms, further extend sociocultural interactions beyond physical classrooms. By leveraging community knowledge and fostering communicative competence, sociocultural approaches enrich STEM learning, especially for underrepresented groups.

Moreover, sociocultural theory aligns strongly with collaborative STEM pedagogies such as inquiry groups, engineering design teams, and project-based learning communities. Research indicates that such collaboration helps students develop communication, negotiation, and shared problem-solving capacities—competencies essential for modern STEM fields (Roehrig et al., 2021). Peer mentoring structures further support knowledge diffusion, enabling advanced learners to model disciplinary discourse and problem-solving strategies for their peers.

Sociocultural perspectives also support the integration of community and industry partnerships into the STEM curriculum. When students interact with engineers, scientists, or local professionals, they gain access to authentic practices and tools that shape their understanding of STEM disciplines (Bybee, 2013). These partnerships help bridge school-based learning with real-world applications, fostering STEM career awareness and broadening participation—particularly for students historically underrepresented in STEM.

Pedagogical Models Supporting STEM Education

This section discusses some pedagogical models supporting STEM education, as described in Figure 2: experiential learning, inquiry-based learning, and problem-based learning. It also briefly examines interdisciplinary teaching models.

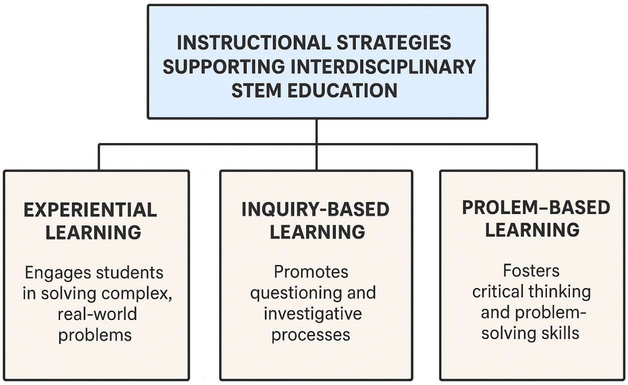

Figure 2. Pedagogical models supporting STEM education

Experiential Learning

Experiential learning emphasises learning through active experience coupled with reflection and conceptualisation (Kolb, 1984). STEM education leverages this through hands-on labs, fieldwork, simulations, maker spaces, and authentic projects. Through direct interaction with materials and phenomena, learners underpin abstract concepts with sensory and practical knowledge, enhancing retention and motivation. Reflective processes encourage learners to consolidate experiences into conceptual frameworks, fostering transfer to new contexts. For instance, robotics projects enable students to test, refine, and iterate designs, embodying experiential learning cycles. This approach supports diverse learning preferences and encourages lifelong learning dispositions.

In middle school mathematics, experiential learning might be enacted through practical activities such as a "market day" simulation where students use currency and budgeting skills to buy and sell goods. By physically handling money and managing expenses, students connect abstract notions of arithmetic and financial literacy to tangible experiences. They reflect on their strategies after the activity, consolidating learning about addition, subtraction, and multiplication within everyday contexts. Such experiential opportunities encourage engagement and retention, making mathematics relevant and fostering transferable skills aligned with STEM educational goals.

Experiential learning environments also support sensory-rich and embodied experiences that help students form durable conceptual understandings (Kolb, 1984). In STEM education, physical manipulation of materials—such as constructing geometric solids, programming robots, or conducting field measurements—helps students bridge the gap between abstract representations and concrete phenomena. These active, hands-on encounters stimulate multiple cognitive pathways, enabling learners to interpret, transform, and apply knowledge in flexible and innovative ways.

Additionally, experiential learning supports the development of STEM identities by positioning students as capable doers and creators. When learners engage in authentic tasks—such as building prototypes, collecting environmental data, or using technology to model real-world systems—they begin to see themselves as mathematicians, scientists, or engineers (Bybee, 2013). This identity development is particularly crucial during middle school years, when students' beliefs about their abilities in STEM often solidify. Experiential approaches, therefore, not only enhance academic learning but also contribute to long-term engagement and persistence in STEM fields.

Inquiry-Based Learning (IBL)

Inquiry-based learning positions students as active investigators who generate questions, seek evidence, and build explanations (Barron & Darling-Hammond, 2008). This approach nurtures scientific thinking and dispositions such as curiosity and scepticism, which are critical in STEM disciplines (Li et al., 2025; Qablan et al., 2024). Through cycles of exploration, hypothesis formation, experimentation, and reflection, learners experience the authentic processes of scientific inquiry. For example, students may investigate environmental phenomena using data-collection and analysis tools, thereby fostering both content knowledge and critical inquiry skills. IBL emphasises student autonomy, engagement, and the development of transferable epistemic practices. It is particularly effective when integrated with interdisciplinary contexts, enabling students to connect concepts across STEM fields.

Inquiry-based learning fosters student curiosity through active investigation and scientific reasoning (Qablan et al., 2024; Vasuki et al., 2016). In a middle school mathematics class, this might involve presenting students with a real-world problem, such as determining the most efficient way to measure ingredients for a recipe, prompting them to generate questions about units and proportions. Students could then collect data by experimenting with different measurement tools, discuss their findings collaboratively, and develop conclusions about volume and ratio relationships. This hands-on, student-led inquiry not only deepens their understanding of mathematical concepts but also develops critical thinking and communication skills essential to STEM learning.

Research shows that IBL environments help students develop epistemic agency, enabling them to take ownership of how knowledge is generated and validated (English, 2016). This is particularly important in STEM disciplines, where inquiry mirrors authentic scientific and mathematical practices. When learners ask their own questions, design experiments, and justify conclusions with evidence, they engage in forms of disciplinary thinking that extend beyond rote procedures. Such environments cultivate curiosity, resilience, and a willingness to grapple with uncertainty—a hallmark of expert STEM reasoning.

Furthermore, IBL supports interdisciplinary STEM integration by encouraging students to draw upon knowledge from multiple domains when investigating complex phenomena (Vasuki et al., 2016). For example, when students explore population growth using real datasets, they may integrate mathematical modelling, technological data visualisation, and scientific reasoning. This interdisciplinary inquiry helps learners recognise the interconnectedness of STEM fields and strengthens their ability to apply mathematics and science concepts in meaningful contexts (Honey et al., 2014). Through these experiences, IBL becomes not only a pedagogical approach but also a bridge connecting theory with real-world STEM applications.

Problem-Based Learning (PBL)

Problem-based learning engages students with complex, real-world problems often lacking clear-cut solutions (Hmelo-Silver, 2004). PBL aligns well with STEM's applied nature by encouraging learners to employ scientific principles, engineering design, technological tools, and mathematical reasoning in integrative ways. Learners develop collaboration, communication, and self-directed learning skills by working in teams to iteratively define problems, gather information, generate solutions, and reflect on results. This model promotes creativity, resilience, and systems thinking necessary for innovation (Kirişci et al., 2020). For example, students may design sustainable energy solutions requiring knowledge from physics, chemistry, and social sciences. PBL also fosters metacognitive awareness, as learners monitor their reasoning and problem-solving strategies.

Problem-based learning in a middle school maths setting could involve students working in groups to solve an authentic problem, like designing a classroom garden with limited space. Students would engage in calculating area and perimeter, applying knowledge of geometry and measurement, while considering constraints such as space and budget. Throughout the project, learners propose multiple solutions, evaluate their feasibility using mathematical reasoning, and present their final designs to peers or staff. This process emphasises collaboration, integration of mathematical concepts with real-world contexts, and develops problem-solving and decision-making skills, reflecting the integrative nature of STEM disciplines.

PBL also plays a critical role in developing students' metacognitive capacities (Downing et al., 2011). As learners navigate complex, open-ended problems, they must plan strategies, monitor progress, and evaluate the effectiveness of their solutions—skills essential for expert STEM performance (Hmelo-Silver, 2004). These reflective practices enable students to become more self-directed and adaptable, strengthening their ability to transfer knowledge across diverse situations. Moreover, PBL's emphasis on iterative refinement mirrors the design cycles used by engineers and scientists, helping students internalise authentic STEM processes.

In addition, PBL facilitates equity-oriented STEM education by allowing learners to leverage personal experiences, cultural knowledge, and community contexts when approaching problems (Jackson et al., 2021). When students design solutions for issues such as energy efficiency, water conservation, or local transportation, they draw on both disciplinary knowledge and lived experiences (Kelley & Knowles, 2016). This enhances relevance and motivation, particularly for students who may feel disconnected from abstract or decontextualised STEM instruction. Thus, PBL not only strengthens cognitive outcomes but also fosters inclusion and engagement across diverse learners.

Interdisciplinary Teaching Models

Interdisciplinary STEM education integrates methodologies, concepts, and practices from multiple disciplines, creating cohesive learning experiences that mirror real-world challenges (Nugraha et al., 2024). Such models dismantle siloed subject barriers, offering thematic units, team teaching, and project-based approaches that require synthesis across science, technology, engineering, and mathematics. For example, a water quality project may encompass chemistry testing, statistical analysis, engineering remediation, and technological data logging. Interdisciplinary teaching supports higher-order thinking, creativity, and transferability. It necessitates collaborative planning among educators, flexible curriculum frameworks, and pedagogies promoting integrative reasoning in diverse classrooms.

Interdisciplinary teaching in a middle school maths class could involve a project linking mathematics with science and technology, such as analysing data from a weather station to predict rainfall. Students collect temperature, humidity, and precipitation data, then use statistical methods to identify patterns and make predictions. Technological tools like spreadsheets or graphing software support data analysis, while scientific concepts explain atmospheric conditions. This interdisciplinary approach helps students see mathematics as a tool for understanding and solving real-world problems, integrating knowledge across disciplines and developing skills such as data literacy, critical thinking, and technological competency.

Interdisciplinary teaching models are grounded in the understanding that real-world problems seldom fall neatly within disciplinary boundaries. Effective STEM instruction therefore integrates concepts and practices from multiple domains, helping students develop systems thinking and the ability to synthesise diverse forms of knowledge (Nugraha et al., 2024). Such integration enhances students' capacity to recognise patterns, evaluate trade-offs, and generate holistic solutions—competencies central to STEM innovation.

Moreover, interdisciplinary STEM models require collaborative planning among teachers, which strengthens instructional coherence and expands opportunities for student learning. When mathematics, science, and technology teachers co-design units—such as sustainability investigations, engineering design challenges, or data-driven scientific inquiries—students experience a unified learning trajectory rather than fragmented lessons (Roehrig et al., 2021). This coherence improves both conceptual understanding and student engagement, ensuring that STEM learning feels purposeful, connected, and relevant.

Example Lesson Plan: Mathematical Modelling in Middle School Mathematics

Mathematical modelling is widely recognised as a core process in STEM education because it integrates mathematical reasoning with real-world scientific, technological, or engineering contexts. This approach enables students to use mathematics as a tool to represent and solve authentic problems, develop analytical thinking and problem-solving skills, and apply interdisciplinary knowledge relevant to STEM fields.

Mathematical modelling tasks also help students understand the iterative nature of mathematical thinking. As learners refine assumptions, adjust variables, or reinterpret data, they engage in cycles of reasoning similar to those used by scientists and engineers (English, 2016). This iterative process deepens understanding by prompting learners to reflect on both the accuracy and limitations of their models. Such experiences develop flexibility and resilience—skills that are indispensable for tackling the uncertain, complex problems that characterise STEM careers.

Furthermore, modelling provides opportunities to incorporate digital tools such as spreadsheets, dynamic graphing applications, or simulation environments. These tools allow students to visualise patterns, test scenarios, and analyse large datasets, strengthening their data literacy and technological fluency (Honey et al., 2014). Integrating technology not only enhances conceptual understanding but also mirrors contemporary STEM practices where modelling is often computationally supported. Therefore, modelling tasks serve as a bridge between school mathematics and real-world technological problem-solving.

Research and educational frameworks emphasise that mathematical modelling activities are open-ended, interdisciplinary problem-solving tasks that foster critical STEM competencies such as creativity, collaboration, and flexible use of mathematics and science concepts (Doğan et al., 2019; Fitzallen, 2015; Kertil, 2016). The lesson plan's focus on modelling real-world scenarios using algebraic expressions and equations fits well within the characteristics of STEM teaching and learning. Appendix A provides a sample STEM lesson plan to be used in middle school mathematics classes.

Epistemological Foundations and STEM Curriculum

The epistemology of STEM education prioritises empirical inquiry, problem-solving, and the iterative nature of knowledge construction. It rejects static views of learning in favour of dynamic, adaptive understandings that empower learners to question, investigate, and innovate (National Research Council, 2012). STEM curricula rooted in these epistemological principles emphasise authentic tasks, integration of disciplines, and real-world relevance. Such curricula foster competencies that transcend content mastery, including metacognition, ethical reasoning, and technology fluency, preparing learners for complex future challenges.

In addition, epistemological perspectives shape teachers' instructional decisions by influencing what counts as legitimate knowledge and learning in STEM classrooms. When teachers adopt an inquiry-oriented epistemology, they prioritise student questioning, experimentation, and justification over memorisation or procedural fluency (Bybee, 2013). This shift establishes learning environments where uncertainty is welcomed and failure becomes a productive part of knowledge building. As a result, students develop more authentic STEM dispositions, including curiosity, open-mindedness, and critical evaluation of evidence.

Epistemologically grounded STEM curricula also encourage integrative thinking by promoting connections across disciplines rather than treating knowledge as compartmentalised. Such curricula emphasise big ideas, crosscutting concepts, and real-world phenomena that cannot be understood through a single disciplinary lens (Roehrig et al., 2021). This orientation helps students recognise the coherence of STEM knowledge and apply it flexibly in diverse contexts. Ultimately, epistemology serves as the foundation that aligns standards, teaching practices, assessments, and learning environments toward a unified vision of meaningful STEM learning.

Developing 21st-Century Competencies through STEM

STEM education is uniquely positioned to foster essential competencies for success in a knowledge-based, interconnected world. These include:

- Critical Thinking and Analytical Reasoning: Learners evaluate evidence, synthesise information, and reason logically when solving complex STEM problems.
- Collaboration and Communication: STEM projects often require teamwork, negotiation, and clear articulation of ideas to diverse audiences.
- Creativity and Innovation: STEM pedagogy encourages imaginative problem-solving, iterative design, and original thinking.
- Technological Literacy: Familiarity with current digital tools, coding, and information technologies is embedded throughout STEM curricula.
- Adaptability and Lifelong Learning: STEM learners develop resilience and a growth mindset essential for continuous learning amid evolving scientific and technological landscapes.

Embedding these competencies involves integrating theory with practical application through pedagogies that promote active engagement, reflection, and interdisciplinary learning. That is to say, these competencies are embedded through pedagogical strategies that align with the theoretical foundations outlined previously, ensuring learners are well-equipped for societal and workforce demands.

Furthermore, research indicates that 21st-century competencies thrive when learners participate in open-ended, authentic STEM tasks that require them to plan, reason, test, and adapt their ideas. For example, engineering design challenges cultivate creativity and systems thinking as students iterate solutions under real constraints (Kelley & Knowles, 2016). Similarly, collaborative modelling projects strengthen communication and teamwork while encouraging students to negotiate meaning and articulate mathematical reasoning. These experiences reflect the competencies valued in modern STEM professions and global citizenship.

The development of these competencies is also closely tied to students' sense of agency and identity within STEM fields. When learners see themselves as capable contributors—designers, analysts, problem solvers—they are more likely to persist in STEM learning and careers (Bybee, 2013). Classroom structures that promote student voice, leadership roles, and reflection support this identity development. Thus, STEM education contributes not only to skill acquisition but also to the cultivation of empowered, confident learners prepared for participation in an innovation-driven society.

Discussion

This chapter has delineated the theoretical foundations and pedagogical models that robustly support STEM education. Constructivism, cognitive load, and sociocultural theories provide complementary insights into how knowledge is constructed, processed, and mediated. Pedagogical models such as inquiry-based and problem-based learning operationalise these theories into effective, learner-centred STEM instruction that cultivates essential skills and dispositions. Epistemologically grounded STEM curricula orient toward authentic, integrative tasks that develop adaptive and innovative learners.

Future directions involve leveraging emerging digital technologies, enhancing culturally responsive pedagogies, and systematically researching the impact of these theoretical applications on diverse learner outcomes. Professional development for educators should focus on deepening understanding of these theories and translating them to dynamic classroom practices.

Moreover, the integration of these theoretical perspectives underscores the need for coherence across curriculum design, classroom practice, and assessment. Without alignment, students may experience fragmented instruction that undermines the goals of STEM education (Honey et al., 2014). For instance, if assessments focus solely on procedural skills while instruction emphasises inquiry and modelling, learners receive conflicting messages about what matters in STEM. Therefore, future efforts should prioritise assessment systems that capture inquiry processes, collaborative problem-solving, and interdisciplinary reasoning.

Additionally, the discussion highlights the importance of context-sensitive STEM implementation. What works in one cultural or institutional setting may not translate directly to another, underscoring the need for adaptable models that respect local needs and resources (Roehrig et al., 2021). Collaboration among teachers, researchers, community partners, and policymakers will be essential to designing sustainable and equitable STEM learning ecosystems. Such collaboration can help ensure that STEM education continuously evolves to meet the demands of a rapidly changing world.

Conclusion

STEM education's theoretical foundations form a vital base for designing engaging, effective, and inclusive learning experiences. By synthesising constructivist, cognitive, and sociocultural perspectives with inquiry-driven and interdisciplinary pedagogical models, STEM education prepares learners for the complexities of contemporary society and future challenges. A thorough understanding of these underpinnings empowers educators and policymakers to cultivate learners equipped with critical competencies — fostering innovation, equity, and lifelong adaptability in STEM domains.

To conclude, the theories and pedagogical models explored in this chapter provide a framework for understanding how students learn, how teachers can support learning, and how curricula can be structured to promote meaningful engagement. When implemented coherently, these approaches transform classrooms into dynamic environments where learners collaborate, investigate, and apply knowledge across disciplines. Such environments advance the broader goals of STEM education, including workforce readiness, scientific literacy, and global competitiveness.

Looking ahead, STEM education will continue to evolve in response to technological advancements, societal needs, and emerging research. Ensuring that this evolution remains grounded in robust theoretical foundations will be crucial for maintaining quality and equity. Educators, researchers, and policymakers must therefore work collectively to refine practices, integrate new insights, and expand opportunities for all learners to succeed in STEM fields. With continued commitment, STEM education can play a transformative role in shaping a more innovative and equitable future.

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Appendix A. Sample STEM Lesson Plan: Mathematical Modelling in Middle School Mathematics

Title of Lesson:

Modelling Real-World Problems Using Algebraic Expressions and Equations

Grade Level:

Middle School (Grades 6–7)

Duration:

2 class periods (40 minutes each)

1. Learning Objectives

By the end of the lesson, students will be able to:

1. Construct and interpret algebraic expressions to represent real-world scenarios.
2. Develop and refine mathematical models using provided or collected data.
3. Collaborate to analyse constraints, generate possible solutions, and justify reasoning.
4. Use digital tools (e.g., spreadsheets, graphing software) to test and visualise model outcomes.
5. Communicate modelling processes and solutions using appropriate mathematical language.

2. STEM Connections

STEM Strand	Connection in Lesson
Science	Understanding real-world phenomena (e.g., resource use, temperature changes).
Technology	Use of spreadsheets, simulations, or graphing tools to model data.
Engineering	Considering constraints, optimising solutions, iterative refinement.
Mathematics	Formulating equations, identifying patterns, analysing variables and relationships.

3. Materials Needed

- Laptops/tablets with spreadsheet or graphing software
- Realistic problem scenario sheet (e.g., water consumption, school garden budget, bus route analysis)
- Grid paper and markers

- Data tables (sample or student-generated)
- Projector or smart board

4. Lesson Procedure

A. Introduction (10 minutes)

- Teacher presents a real-world scenario (e.g., planning cost-efficient lunch packages, designing a rectangular garden, analysing weekly water use at school).
- Students brainstorm factors, constraints, variables, and unknowns.
- Discuss: *"How can mathematics help us make predictions or decisions about this situation?"*

B. Exploration & Data Modelling (20 minutes)

- Students work in small groups to:
  - Identify variables and write algebraic expressions.
  - Create a table of values (manually or digitally).
  - Represent the relationship using graphs or diagrams.
- Teacher circulates, prompting students to explain and justify their reasoning.

C. Model Refinement (30 minutes)

- Students test their expressions using real or simulated data.
- Groups adjust assumptions or constraints based on outcomes.
- Each group prepares a concise modelling summary:
  - Variables
  - Assumptions
  - Mathematical model (expression or equation)
  - Interpretation of results
  - Limitations of model

D. Presentation & Discussion (15 minutes)

- Groups present solutions; class compares model differences.
- Discussion prompts:
  - "Which model best fits the scenario?"
  - "How do assumptions change the model's accuracy?"
  - "What would you do differently with more data?"

5. Assessment Tools

A. Formative Assessment

- Teacher questioning during group work

- Student modelling notebooks
- Observation checklists for collaboration and reasoning

B. Summative Assessment Rubric

Criterion	Excellent (4)	Proficient (3)	Developing (2)	Beginning (1)
Model Construction	Clear, accurate expressions; strong variable reasoning	Mostly accurate expressions	Partial model; variables unclear	Incorrect or missing model
Data Use & Representation	Accurate tables/graphs; appropriate tools	Minor errors; adequate use	Limited or partially incorrect	Missing or incorrect
Interpretation & Refinement	Insightful analysis; thoughtful revisions	Adequate analysis	Limited reasoning	Minimal or no interpretation
Communication	Clear, precise explanation	Understandable explanation	Partial explanation	Hard to follow

6. Differentiation Strategies

- **Support:** sentence starters, expression templates, worked examples
- **Extension:** additional constraints (budget caps, optimisation tasks), multi-variable scenarios
- **Multimodal learning:** visual graphs, manipulatives, tech tools, verbal reasoning

7. Teacher Reflection Questions

1. Were students able to meaningfully connect mathematics to the real-world scenario?
2. Which parts of the modelling cycle were most challenging for them?
3. How did collaboration influence student understanding?
4. What changes would improve the modelling task in future lessons?

8. Sample Student Worksheet (Extract)

Problem Scenario:

Your school wants to design a small rectangular garden with fencing on three sides (the building forms the fourth side). The garden must maximise area with a fixed fencing length of 24 meters.

1. Define variables for width (w) and length (l).
2. Write an expression relating w and l given the fencing constraint.

3. Create a table showing possible (w, l) pairs.
4. Graph the relationship.
5. Determine which dimensions give the maximum area and explain why.

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Chapter 2

Constructivist Approaches in STEM Education

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Chapter Highlights

This chapter summary provides the reader with a quick and general overview by summarizing key points about constructivist approaches to STEM education.

- Fundamental components of STEM education - integration of science, technology, engineering, and mathematics; problem-based learning, project-based learning and collaborative learning.
- The role of constructivist approaches in STEM education – Evaluation of cognitive, social and radical constructivist perspectives on learning knowledge.
- 21st century skills and STEM education - The contribution and impact of transversal competencies on STEM education
- Advantages and limitations of the constructivist approaches – Positive and negative aspects of constructivist approaches from the teachers' and students' point of view
- Future Directions and Recommendations – Integrating technology into the educational environment, providing teacher training on STEM education and the application of constructivist methods, and providing the necessary infrastructure.

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Introduction

In the 21st century, which is in a constant state of technological development and change, it is crucial to utilize methods in education that include skills like creative thinking, critical thinking, problem solving, and constructing information by processing it in collaboration with peers, instead of traditional teaching methods in which students passively receive information. As is well known, in traditional teaching methods, individuals learn information as it is conveyed to them and are passive in this process (Jonassen, 1991; Amirova, 2025). STEM (Science, Technology, Engineering, and Mathematics) education and constructivist approaches also include skills that will help the individual keep up with this changing situation and not fall behind the times. When considered in this context, these approaches, which see learning as a process and advocate active learning, are based on 21st century skills (Amirova, 2025).

"*21st century skills*" has a broad meaning in terms of content. Vista (2020) also expresses this term as a very broad set of skills. Ananiadou & Claro (2009) describe 21st century skills as the use of higher-order cognitive skills like analysis and reasoning to understand and solve events that one enjoys. Individuals with 21st century skills will develop different perspectives on events, situations and problems, enabling them to better align to the rapidly changing technological world and the conditions in which the individual finds herself/himself. In addition, an individual with 21st century skills can take on a guiding role in society by looking at events from a critical and innovative perspective and producing solutions appropriate to the needs and requirements of the society in which she/he lives. Based on this, it can be stated that 21st century skills are in a close relationship with STEM education.

STEM education is an approach that brings together the disciplines of Science, Technology, Engineering and Mathematics, and interest in STEM education is increasing day by day. One of the main reasons for this situation is that students are prepared for the changing world in every field (Tytler, 2020). Because STEM education enables individuals to find various, distinctive solutions to the problems that they encounter (Altunel, 2018). By doing so, STEM education promotes positively to the advancement of creativity by empowering the individual to think analytically. Additionally, in STEM education, the individual looks at problems that are intertwined with daily life with a critical eye and approaches them with a problem-solving perspective, allowing them to look at events from different perspectives. With STEM education, individuals have the prospect to put their knowledge and skills into practice (Salinger & Zuga, 2009). Therefore, these features in STEM education need to be addressed and supported with a modern/constructivist approach. Considering all these skills, it can be said that STEM education and constructivist approaches have fundamentally similar features. Because in both STEM education and constructivist approaches, the individual is active in the process of processing information, making sense of it, constructing information, and focusing on problem solving.

In this chapter, constructivist approaches in STEM education, their basic principles, philosophical and psychological foundations, constructivist teaching models used in STEM education, and student - teacher characteristics are discussed in detail. Additionally, the advantages, limitations and challenges of implementing STEM education and constructivist approaches in educational settings were discussed. Finally, in line with the main intention of the study, the measurement and evaluation process of constructivist approaches in STEM education was examined.

What is constructivism?

Since the end of the 20th century, the philosophy of constructivism has increased its importance. It is possible to talk about various reasons for the increasing popularity of constructivism. For instance, in parallel with the development of technology, individuals are expected to have various skills such as being more creative and having better problem-solving skills in business life. Similarly, Arslan (2007) states that one of the most important philosophies affecting educational practices is constructivism. He cited the primary reason for this as a desire to find solutions to the qualitative problems in countries' education systems. Because developed societies no longer require individuals to have only in-depth knowledge. On the contrary, they require individuals to possess high-order skills such as constructing and interpreting information, analytical thinking, and problem-solving. The constructivist approach also bolsters the advancement of 21st-century competencies, like problem-solving, critical thinking, and creativity, which are at the core of STEM education (English, 2016).

In the age of information and technology we live in, it is not expected for individuals to be passive recipients. Both the social structure in which the individual lives, technological developments and the changing business life have made it necessary for the individual to learn actively, to have problem-solving skills and an innovative perspective, and to construct new knowledge by making sense of the information in the learning process. All these necessities have made it necessary to abandon the understanding of education to approaches in which knowledge is constructed rather than traditional models and methods.

Constructivism can be expressed as the individual learning new information by associating it with his/her existing knowledge and thus new learning occurs in the individual (Gömleksiz & Elaldı, 2011; Sherman & Kurshan, 2005; Noureen, Arshad & Bashir, 2020; Daley, 2001). In this process, Bhardwaj et al. (2025); Duffy and Cunningham (1996) define learning as a process in which a person actively creates meaning from their experiences and builds on the knowledge she/he has. In short, the constructivist approach is meaningful learning by constructing students' own learning (Gao et al., 2013; Kouicem & Nachoua, 2016). In the epistemological context, the constructivist approach argues that the individual does not receive knowledge directly, but goes through a mental process and constructs it depending on the individual's experiences (Prawat, 1992). In this context, learning is a phenomenon that subjectively expresses continuity for the individual. In this process, knowledge is not certain but subjective. In other words, knowledge does not represent absolute truth; it is the individual's way of making sense of and interpreting the world.

Even though constructivism became popular in education from the late 19th century onwards, its history dates back to Socrates in the 5th century (Brooks & Brooks, 1999; Busbea, 2006). Other prominent pioneers of constructivism are Giambattista Vico (1668-1744), Jean-Jacques Rousseau (1712-1778), Immanuel Kant (1724-1804), Jean Piaget (1896-1980), John Dewey (1859-1952), Bruner (1915-2016), Vygotsky (1896-1934) and Ernst von Glasersfeld (1917-2010). Hanley (2005) stated that Giambattista Vico was a philosopher who attributed similar meanings to modern constructivism and brought a new standpoint to epistemology with his work "De antiquissima Italorum sapientia"; he stated that individuals can only comprehend what they construct and that "an individual knows to the extent that he can explain it" (as cited in Arslan, 2007).

Kant (1960) expresses two views regarding knowledge. These are: knowledge developed through logical analysis of actions and objects; knowledge resulting from the individual's experiences. According to the first view, knowledge is formed after learning experience; according to the second view, knowledge is formed together with experiences. According to both views, it is necessary to have a knowledge base in order to construct new knowledge. The existing knowledge possessed by the individual influences his/her interpretation of the knowledge to be acquired later, making sense of it and constructing it (as cited in Busbea, 2006). With these views, Kant stated that individuals are not passive recipients in the process of acquiring knowledge, but rather interpret knowledge as a consequence of their experiences, thus sharing the same thought with Giambattista Vico and expressing today's constructivist approach. Because, in both the theory of Giambattista Vico and Kant, as well as in today's constructivist approach, in order to acquire new knowledge, there must be a pre-existing, existing knowledge base.

One of the most important pioneers of the constructivist approach in the 20th century was Jean Piaget. He served a leading role in the enhancement of constructivist philosophy and in transcending the traditional paradigm of how individuals acquire knowledge. From an epistemological perspective, many thinkers have answered questions such as *"What is knowledge?"* and *"Is knowledge certain?"* from a universal perspective regarding the acquisition of knowledge, and within this framework, they have thought independently of the *"human subject".* Instead of these conventional questions, Piaget asked the more pragmatic question, "How does an individual manage to learn something called knowledge?" (von Glasersfeld, 1998). Piaget was more interested in how knowledge is created and formed. In other words, Piaget's understanding of constructivism is related to cognitive theory (Arslan, 2007; Busbea, 2006). *"Cognitive constructivism"* advocates the thesis that individuals construct knowledge through their own experiences. According to cognitive constructivism, individuals process information but cannot use the incoming information directly. Piaget (1950) states that knowledge is not obtained ready-made from the outside world, but that the individual creates knowledge by associating it with existing knowledge and filtering it through his or her own mental filter; and that as the individual grows older or develops mentally, his or her mental structure also develops.

Another sort of constructivism is "social constructivism," of which Vygotsky is considered the founder. Vygotsky places more emphasis on the social dimension of learning. In this respect, it differs from Piaget, who did not associate learning with social interaction (Raza et al., 2023). Vygotsky (1978) pay attention to the close interrelation between learning and development; states that social interaction helps children progress by keeping their development always alive. In social constructivism, the individual can learn phenomena that she/he cannot learn alone through her/his social and cultural environment (Kouicem & Nachoua, 2016). In other words, it can be stated that learning is a social process rather than an individual process. Vygotsky (1978) argues that individuals learn through social interaction and thus changes occur in individual behavior over time. He also suggests that it is possible to refine students' problem-solving skills through social interaction. In this context, social constructivism offers individuals the opportunity to evaluate the information they obtain from different perspectives. *The "Zone of Proximal Development (ZPD)"* has an important place in social constructivism. Vygotsky (1978) delineates the zone of proximal development as the development of underdeveloped or deficient skills by individuals who are better at these skills under the guidance or in cooperation with competent individuals. However, students should be guided by adults in this process (Busbea, 2006). Namely, cooperation or guidance is important in this process. To sum up, social constructivism argues that individuals develop the skills they lack by observing competent individuals through social interaction (Zhou, 2020).

Another significant constructivist philosopher is Bruner. According to Bruner's constructivist view, students are actively involved in the instructional process and develop their own solutions to the problems they encounter (Barth, 2015). Like Piaget, Bruner also states that knowledge is configured through active involvement by the individual. During the process, instead of directly receiving the information given by the teacher, the student first groups the information and then organizes and reconstructs it (Zhou, 2020). According to Bruner (1960), children learn information in three ways: action-based, visual-based, and language-based. In action-based learning, the child learns by experiencing, doing and living; in visual-based learning, the child learns with pictures and visuals; in language-based learning, the child learns with words, concepts and symbols. Bruner's constructivist theory expresses how students learn and how knowledge is represented by students (Liu & Matthews, 2005). When we examine Bruner's constructivist theory, the student is basically active. The student produces new concepts and ideas using the representation of the information presented to her/him, and this process is affected by culture (Zhou, 2020). In this respect, we can say that Bruner's theory of constructivism has both a cognitive aspect and a social aspect.

"Radical constructivism" developed by Von Glasersfeld can be expressed as the fact that knowledge does not reflect objective reality from an ontological perspective, but rather the arrangement and organization of the world in which the individual creates knowledge through experiences (Von Glasersfeld, 1984). Here, the individual constructs the world without realizing it. Von Glasersfeld characterizes radical constructivism as a break from traditional epistemology. In this context, in radical constructivism, knowledge is not

certain; knowledge is constructed by the individual through experiences during the developmental process.

To summarize cognitive constructivism, social constructivism, constructivist learning and radical constructivism:

Table 1. Comparison of cognitive, social, constructivist learning and radical constructivism

Cognitive Constructivism (J. Piaget)	Social Constructivism (L. Vygotsky)	Constructivist Learning (J. Bruner)	Radical constructivism (E. Von Glasersfeld)
• The individual constructs knowledge through his/her own experiences. • There is a cognitive process. • Knowledge is not certain, it is subjective. • Assimilation and adaptation are important. • The teacher guides the student in the process of constructing knowledge.	• Knowledge is built through social and cultural interaction. • The zone of proximal development (ZPD) is important. • In cases where the individual is deficient, he/she can correct the deficiencies by observing competent individuals. • The teacher acts as a guide.	• The learner take an active part in the instructional process. • There are three basic features in learning information: Action (Enactive) based, visual (Iconic) based, language (Symbolic) based • A teacher is someone who facilitates student learning. • Social environment is also efficacious in learning.	• The formation of knowledge depends on the individual's personal experience. • The individual processes and interprets the raw information coming through her/his senses in the mental process. • There is a constant change and development of information.

Constructivist Teaching Models Used in STEM Education

In the 21st century world, which is rapidly developing and changing in every field, it is a necessity for individuals to constantly follow the changes and developments. However, due to these rapid developments, it is not possible for individuals to know and keep in mind everything. Under these circumstances, it is significant for the individual to *"learn how to learn"* rather than knowing everything. *"Learning to learn"* is only possible with the active engagement of students in the instructional process. There are various teaching models that enable individuals to learn actively. Some of these are: Problem-Based Learning, Project-Based Learning, and Collaborative Learning.

Problem-Based Learning

Problem-based learning (PBL) is one of the active learning methods in which students solve realistic and complex life problems in collaborative groups under the guidance of the teacher (Allen et al., 2011). In PBL, instead of simply learning information, students are encouraged to work in small groups to develop their skills and attitudes positively (Woods, 2008). Therefore, PBL is theoretically based on a constructivist approach.

PBL was developed in the medical field in the late 1960s (Wood, 2008). It was first used by Howard Barrows at McMaster University in Canada (Barrows & Tamblyn, 1980) and later at the University of New Mexico. Afterwards, It has been utilized in a variety of fields like engineering and architecture (Keenahan & McCrum, 2020).

It is possible to mention six basic features of the problem-based learning approach. These are:

- Problem-based learning is learner-focused.
  - Small groups are formed by teachers during the students' learning process.
  - Teachers are guides and have a facilitating role in the instructional process.
  - Problems in the instructional process encourage students to learn.
  - Through problems, students gain problem-solving skills.
  - In instructional process, students take responsibilities for learning and learn new things (Mayer & Greeno, 1972, as cited in Jaganathan; Bhuminathan, & Ramesh, 2024).

When the given basic features are examined, in PBL, the individual actively constructs knowledge during the problem-solving process. In addition, they have the opportunity to learn cooperatively in small groups. This situation plays a positive role in both the learning and socialization of the individual. The fact that teachers act as guides in the learning-teaching process allows students to assume responsibilities for their own learning and decide what, when and how they will learn. In this way, individuals will gain self-confidence in real life and will be more successful by finding different solutions to the problems they encounter.

Kaptan and Korkmaz (2001) list the process steps in problem-based learning as follows:

- Recognizing and defining the problem
- A complete statement of the problem
- Determining information about the problem
- Determining the necessary resources
- Identifying the alternative solutions

- Analyzing the identified solutions
- Presenting the solution

In problem-based learning, the problems presented to students must have certain characteristics. Duck et al. (2001) list these features as follows:

- Problems should be interesting to students.
- Problems should encourage students to learn.
- The problem should be devised in a way that learners can solve it cooperatively in groups.
- Problems must be interconnected.
- Problems must be intertwined with real life.

In problem-based learning, the teacher is in a position to learn with the students and guide them, rather than presenting ready-made information. In this process, he/she is in a position to facilitate the process for the students and motivate them when it's necessary. In this process, the teacher assigned a task or scenario to the students. In this process, students try to solve the problem presented to them in small groups. At the outset of the task, students do not have any idea about the issue. Afterwards, students conduct in-depth research on the problem presented to them and produce solutions to the problem (Kaptan & Korkmaz, 2001). In this process, the student acquires high-ordered cognitive skills by actively participating.

Project-Based Learning

Project-based learning (PjBL) approach is a method that provides permanent learning for the individual. As the name suggests, this method prioritizes the individual's thinking, imagining, analyzing, and developing projects or designs. PjBL is an approach that places the learner at the central position in the instructional process, includes real-life problems, and provides the student with high-ordered cognitive skills. In this respect, it appears as a method that prepares the individual for social life. In this approach, student's involvement in the instructional process is of utmost importance.

In project-based learning, projects can be expressed as intricate assignments based on questions and problems that challenge learners (Mergendoller & Thomas, 1999). In this respect, PjBL has an important place in helping students acquire higher-ordered cognitive skills such as analysis and synthesis. In this process, students can work individually or in groups.

PjBL is closely associated with the philosophy of pragmatism and progressivism in education. Because in both PjBL and pragmatism and progressivism, the student is involved with real-life problems. Progressivism argues that education is life itself (Vatansever Bayraktar, 2015).

In order for a project to be defined as "Project Based Learning", it must have certain characteristics. Thomas (2000) expresses these features as follows:

- PjBL projects are at the centre of the curriculum, not at the periphery. What is meant here is that PjBL projects ought to occupy a central position in the instructional process and that projects cannot be complementary activities to the learning process.
- PjBL projects focus on questions and problems that challenge students to contemplate the core basics and concepts of a discipline. To put it differently, learners acquire basic concepts and principles not only by reading but also by experiencing them through projects.
- Projects engage students in a constructive inquiry process. Research, on the other hand, is purposeful and enables students to learn actively through activities such as questioning, creating knowledge and finding solutions.
- Projects are significantly student-centered. PjBL projects offer students greater autonomy. Students freely plan their projects, deciding what to do, how to do it, and when. In short, the student is fully responsible for the entire process.
- PjBL projects should be relevant to real life, not school settings. Projects should facilitate learners with genuine life exposure.

Advantages and Disadvantages of Project-Based Learning

The PjBL approach helps students acquire various higher- ordered cognitive competencies like problem solving and data analysis (Dori & Tal, 2000). Öztürk and Ada (2006) express the advantages of PjBL as follows:

- It enables students to improve their learning skills.
- It provides lifelong learning.
- Working in groups supports cooperative learning.
- It allows students to use different dimensions of intelligence.
- It provides feedback on student performance.
- It helps students develop problem-solving skills.
- It contributes students with the avenues to apply the knowledge and competencies they have learned with PjBL in different subjects.
- It provides students with various competencies like the ability to use technology, cognitive process skills, various life skills, and self-control skills.

In addition to these advantages, they also stated their disadvantages as follows:

- The teacher's responsibility and workload increases.
- The time allocated for learning may increase.
- If the boundaries of the research are not well defined, there will be deviation and dispersion in the subject.

Collaborative Learning

Cooperative learning can be defined as a group of learners work as a team to accomplish a certain target. In cooperative learning, students in small heterogeneous groups help each other learn, and in this way, positive engagement develops among students and positive development occurs in students' communication and social skills (Watson, 1992). At the same time, as a result of students working in groups, the focus of cooperative learning is on students' ability to make observations, to display appropriate attitudes and behaviors within the group, to establish social interactions with group members, and to develop friendships (Cartwright, 1993). Johnson, Johnson and Taylor (1993); Panitz (1999) also stated that the cooperative learning approach improves students' self-esteem, allows students to take an active role in the teaching-learning process, and is an alternative evaluation method for evaluating students.

Cooperative learning was first written by Deutsch in 1949. Pioneers of cooperative learning include Stuart Cook, Millard C. Madsen and Spencer Kagan, Robert Slavin, Jerome Bruner and J. Richard Suchman, and Frederic Skinner. In addition to these researchers, David W. Johnson and Roger T. Johnson established the *"Center for Collaborative Learning"* at the University of Minnesota (Kılbaş et al., 2022). Their main purpose in establishing the center is to conduct research on collaborative learning.

The cooperative learning approach offers various academic, social, and psychological benefits to the individual. Şimşek et al. (2006) list these benefits as follows:

- It improves the student's thinking skills.
- It encourages critical thinking and allows students to express their ideas freely during the discussion process.
- It contributes learners with the avenues to reveal their talents both inside and outside the classroom.
- It assists students in enhancing their oral communication compedencies.
- Collaborative discussions improve students' recall of text content.

- It contributes learners with an exploratory and active learning environment where they can take responsibility for their learning.
- It ensures that students do not see teachers as the sole source of information.
- It helps students think creatively and do research rather than making them compete.

Social benefits of cooperative learning:

- Cooperative learning helps students develop their social interaction methods.
- It gives students a positive understanding of finding answers to problems.
- It helps students acquire a sense of responsibility towards each other and creates different meanings between students and teachers.
- It assists students acquire a sense of empathy.
- It enables learners to come together and form teams to solve problems.
- It helps students develop their leadership skills.
- It helps students establish social relationships with each other.

Psychological benefits of cooperative learning:

- It helps student develop self-esteem and become a qualified individual.
- It encourages students to seek help when needed.

Traditional-Constructivist Classrooms and Teacher-Student Roles

In the 21st century, as traditional methods gave way to constructivist understanding in the education process, a radical change occurred in the roles of students and teachers in the constructivist classroom environment. As is known, in conventional classrooms, the teacher presents information to the learners in depth and students memorize this information by taking notes. With constructivism, the classroom environment has become a place where important ideas are investigated and examined in depth (Prawat, 1992). In other words, constructivist classrooms are an environment where information is constructed rather than memorized. We can compare the constructivist classroom with the traditional classroom in the following way.

Table 2. Comparison of a traditional classroom and a constructivist/modern classroom (Chaika, 2024)

Traditional Classroom	Constructivist/Modern Classroom
• Focuses on memorizing information. • The teacher is positioned at the core of instructional process. • Textbooks, course materials are the main resources. • There is a structure with hierarchy and discipline. • Courses are held according to a fixed curriculum. • The value given to higher-order thinking skills is quite limited. • There is monotony in learning. • The integration of technology in the classroom is very limited. • Standardized exams and tests are used to evaluate students.	• The student is at the center of education. • There is interaction among students in the classroom. • The teacher provides an environment that develops students' creativity and independent thinking during the teaching process. • Encourages students to learn individually. • There is a flexible program. • The teacher integrates technology into the lesson. • Focuses on practical skills. • Process is important in student assessment; projects, presentations and group work are frequently used.

In the constructivist approach, the choice of classroom, in other words, the educational setting is of utmost importance. Because the process of students assimilating, interpreting and constructing information is shaped in this environment. If a suitable learning environment is not provided or created for students, this situation may have negative repercussions on students. In constructivism, where each individual is special, students' interests and needs vary, so students' levels should be prioritized in classroom organization. Cunningham, Duffy, and Knuth (1993) stated that constructivist learning environments should serve the following seven purposes:

- It should provide students with experience and life in the process of constructing knowledge. Students must decide for themselves how they will study the topics they are studying and which methods and strategies they will use in the problem-solving process. The main role of the teacher in this process is to help students in this process.
- Different perspectives and ideas should be taken into consideration. Generally, there is more than one solution to the problems we encounter. Therefore, an environment that provides opportunities for students to evaluate different solution methods should be

designed in a constructivist learning environment.

- Learning should be carried out in real-life contexts and in contexts appropriate to real life. Here, it is stated that the problem-solving activities that students engage in during the learning process at school should be adapted to real-life problems. In other words, it means reflecting a skill that a student learns in the classroom into his or her daily life.
- Students ought to be promoted to take responsibility in the instructional process and to express their own ideas openly. This statement emphasizes that constructivist learning is student-centered and that teachers should counsel and guide students throughout the process.
- The learning process should be supported by social experiences. An individual's rich social life is exceedingly important for his or her mental development. For this reason, students should be in constant interaction with both their teachers and their friends, and the instructional space should be set up in this way.
- Learners ought to be encouraged to access information in different ways and formats. Therefore, using a variety of tools and materials is crucial in the instructional process. Learners ought to be encouraged to learn the subject from different perspectives rather than just written or verbal expression. The learning process should be supported by various materials and tools such as images and videos.
- Students should be encouraged to gain self-awareness in the process of constructing knowledge. In a constructivist environment, it is essential not only for the learner to learn the information but also why and how she/he learns it. Here, it is more important how the student reaches the result, in what way, and by using which strategies, rather than reaching the result of a problem. Therefore, the learning environment should encourage students to gain self-awareness (as cited in Honebein, 1996).

Bada and Olusegun (2015) express the aims of constructivist classes as options for critical and creative thinking, appreciation of practicing diverse teaching approaches, collaborative learning, active role of students, realistic-based activities, exploration of possible solutions and construct knowledge. Raza et al., (2023) also created a symbolic shape for these items.

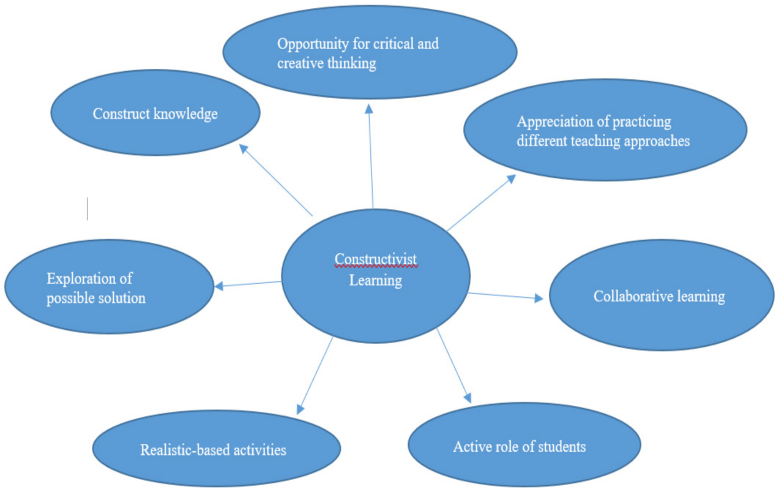

Figure 1. The aims of the constructivist classroom

In traditional methods, there is a teacher-focused situation where the educator is at the center of knowledge (Alam, 2023; Alessa & Hussein, 2023; Chaika, 2024). With constructivism, this situation has turned into a situation where the teacher is more in a guiding (Mishra, 2023) position, associating students' new learning with previous learning (Gömleksiz & Elaldı, 2011; Arslan, 2007; Naylor & Keogh, 1999). In other words, the learning process has become an environment shared by both educators and learner. In this process, the teacher creates a learning environment by taking into account the individual differences and interests of the students. In this learning environment, various teaching strategies such as cooperative learning and drama are applied to help students develop different perspectives on events and situations (Wilson, 1997). Additionally, the educator promotes students' active engagement in the instructional process, ask questions, and learn in depth (Zajda, 2018).

Brooks and Brooks (1999) list the basic characteristics that teachers who adopt the constructivist approach should have as follows: Teachers ...

- care about their students' opinions.
- prepare classroom activities that will challenge students' assumptions.
- create meaningful problems that develop students' interests and curiosity.
- create a classroom environment where students can develop and

ascribe personal meaning.

- organize lessons around "core/primary concepts" and "big ideas."
- view student assessment as part of the process. In other words, assessment is not separate from the activities implemented in the classroom, but rather is a part of them.
- assist learners assume responsibilities for their own learning.
- provide students with real-life tasks.
- do not transfer knowledge to students, but help students construct knowledge.
- encourage learners to be responsible for their own learning and helps them construct knowledge subjectively.
- help students make interdisciplinary connections.

In an environment where the constructivist approach is adopted, it is certainly unthinkable for the student to remain passive and be content with only what is presented to her/him. In contrast, in constructivist education, there is sharing of responsibility in a collaborative environment. Constructivism offers individuals the opportunity to construct their own learning (Alam, 2023; Mondal & Khare, 2023; Noureen, Arshad, & Bashir, 2020; Juvova et al., 2015). In addition, in constructivism, which enables students to approach situations with a critical perspective, it is extremely important to create an environment in which students will take an active role in the learning process and to motivate them for active learning (Mir & Jain, 2015). In constructivist teaching, student characteristics can be listed as follows:

- Students are active in the instructional process.
- Learning is his/her responsibility.
- The student is primarily responsible for constructing knowledge during the learning process.
- Students construct learning subjectively by asking questions to the teacher.
- Students have a researcher, inquisitive and curious personality.
- Students make self-assessment.

Measurement and Evaluation in the Constructivist Approach

In the constructivist approach, student assessment does not consist of paper-and-pencil or test exams as in traditional methods. Because in these types of assessments, students must memorize and recall information. In other words, traditional methods direct students to memorize. In this assessment, it is not possible to measure any higher-ordered cognitive skills of the student. In addition, students may not be able to fully demonstrate their knowledge in the exam due to various reasons (illness, being late for the exam). However, the evaluation that is consistent with the basic philosophy of the constructivist approach is that it is performance-based or process-based. In other words, assessment isn't a quick process; rather, it's an observation of a student's progress over a period of time or the creation of a product. For instance, a student might be asked to prepare a project or give a presentation. Additionally, student self-assessment, peer assessment, and portfolio preparation can be given as examples of the types of assessment used in constructivism. In all of these types of evaluation, the student's development is evaluated and in this process, the student has the opportunity to learn from the mistakes she/he has made.

Advantages and limitations of the constructivist approach

It is possible to talk about many advantages of using constructivism in the teaching process since it has a student-centered structure. However, it is also possible to mention some limitations. Alam (2023) listed the advantages and limitations of constructivism as follows:

Table 3. Advantages and limitations of constructivism (Alam 2023)

Advantages	Limitations
• The individual has the opportunity for personalized learning. • The individual constructs her/his own learning. • The learning process is individual. • It helps the individual to have different perspectives on any subject. • Encourages individuals to work cooperatively. • Active learning is involved. • It enables the individual to learn the subject in depth. • It provides an interesting environment for students. • It provides the individual with critical thinking, problem-solving and interdisciplinary skills. • It helps learners improve their communication skills.	• In a constructivist classroom, the educator spends much time and effort preparing appropriate materials and classroom environment. • Evaluating students is difficult because learning is individual and specific to the student. • Due to the flexible nature of constructivism, it may cause confusion in students who expect clear instructions and directions from the teacher.

Bada and Olisegun (2015) express the benefits of constructivism as follows:

- Students learn more and have fun when they take an active part in the instructional process.
- Constructivist approach allows individuals to learn to think and understand. In other words, the constructivist approach teaches individuals how to think.
- The constructivist approach helps individuals transfer the knowledge and competencies they have acquired to daily life.
- The connection of the activities in the learning process to real life encourages students' participation in the process in a positive way.
- It contributes to the development of students' social and communication skills.

Steakley (2008) also states one of the advantages of constructivism is that learners take an active part in instructional process. Similarly, Li (2025) expresses its advantages as follows: it affects students positively both emotionally and socially, it allows students to learn independently and collaboratively, and it is flexible and adaptable. Besides the advantages of the constructivist approach, Gordon (2009) also points out that teachers need to be pedagogically experts as a limitation. The number of learners in the classroom is essential for constructivist methods to be used effectively in education and serve their purpose. It can be said that it is difficult to apply constructivist methods in crowded classes.

Discussion

In the 21st century, the rapidly developing technology has also changed society's expectations from individuals. The 21st-century world expects individuals to be competent in all areas, to possess high- ordered cognitive competences like interdisciplinary and critical thinking, to have collaboration and communication skills, to keep up with the changing world by following developing and changing technology (Binkley et al., 2010; Kyllonen, 2012); and to have the skills to solve such complex problems when faced with information pollution, misinformation and intertwined problems (Tsai et al., 2023). For these reasons, schools should be institutions that prepare individuals for life, rather than simply being institutions where knowledge is transferred.

STEM, which is formed by combining the first letters of the words Science, Technology, Engineering and Mathematics, is based on an interdisciplinary approach that enables individuals to solve problems, acquire critical thinking competencies, and learn via practical and experiential activities. When considered in this context, constructivist approaches appear to overlap with both 21st century skills and STEM education objectives. The constructivist approach is based on the individual's learning by doing and experiencing, acquiring high-ordered competencies like problem-solving skills in a collaborative environment, and actively constructing knowledge for himself/herself, rather than being passive recipients. For these reasons, building STEM education on constructivist approaches will contribute positively to the development of various 21st century competencies such as creativity, problem-solving skills, critical thinking, and taking responsibility.

When the literature is examined, it is shown that constructivist learning environments lead to a positive increase in students' motivation and academic success (Tsai, 2023; Do et al., 2023). Syamsuddin (2024) concluded in his study that innovative and constructivist-based learning strategies notably increased both students' motivation and academic achievement. The use of project and design-based learning methods in a constructivist learning environment will contribute positively to the development of students in STEM education. Students' active participation in the learning process, collaborating in small groups to produce solutions to problems, and conducting in-depth research (Alam, 2023; Bada & Olisegun, 2015; Steakley, 2008) will prepare them for real life and support their survival in the ever-evolving technological world order.

In STEM education, two or more disciplines are combined in a single teaching unit (Toma et al., 2024). Some difficulties may arise in the process of interdisciplinary integration in STEM education. These challenges can be listed as follows: time and planning (Lin et al., 2025), integrating the STEM curriculum (Yang & Oh, 2024), inadequate teacher training (Yang & Oh, 2024); difficulty in interdisciplinary integration (English, 2016); lack of support from school administrators in encouraging student collaboration in STEM education (Murata, 2002); inflexible course schedules, compulsory courses, and standardized exams (Lesseig et al., 2017). The constructivist approach, which allows individuals to construct their own learning, has some limitations like other approaches. Alam (2023) and Gordon (2009) state that the possibility of the teacher not being able to create an environment based on constructivist learning and not having the necessary pedagogical competence is a limitation in the learning-teaching process. Guzdial (1997), on the other hand, states that learning occurs in the individual's own mental process and in his or her own world of meaning, regarding the constructivist learning process. Based on this, he states that the mental structure of the individual cannot be directly observed, that is, it cannot be tested by experimental means. For this reason, he stated that constructivism is a philosophical approach rather than a scientific and theoretical one. Therefore, he offered a critique of the constructivist approach (as cited in Şimşek, 2004). Similarly, Çetinkaya (2023) states that the constructivist approach is an approach with more philosophical intensity and that there are some question marks about its evaluation as a theory. Çetinkaya (2023) states that it cannot be tested experimentally and is far from scientific evidence. In addition to these statements, it's worth noting that the effective use of constructivist methods and techniques is extremely effective in preparing students for social life. However, using constructivist methods in crowed classrooms is quite challenging.

Conclusion

Constructivist approaches in STEM education offer individuals the opportunity to construct their own learning by providing active participation in the learning process (Ghaour, 2018; Mir & Jain, 2015). Constructivist approaches help individuals acquire higher-ordered cognitive competencies like problem solving, critical and creative thinking (Almulla, 2023). In the constructivist approach, knowledge is subjective, knowledge is not inherent in humans, the individual is active in the learning process, and constructs knowledge subjectively.

Another feature of constructivist approaches is that students construct knowledge by doing and experiencing. During this process, they create solutions to real-life problems or design projects with their friends in small groups. Thus, students have the opportunity to work flexibly in a collaborative environment. Additionally, while working with a group, individuals gain a sense of responsibility and socialize. The teacher is in an important position in preparing and designing a constructivist learning environment (Mir & Jain, 2015). Because the role of the teacher in providing the materials students need, arranging the environment, encouraging students to research and learners' active engagement in the instructional process is of primary importance (Brooks & Brooks, 1999).

Recommendations

The following suggestions were made regarding the use of constructivist approaches in STEM education:

- In classes where constructivist approach is used, appropriate environments and materials should be arranged according to student interests and needs.

- In constructivist classes, the teacher should organize the learning process flexibly and encourage students to do research.
- Since STEM education is important for the development of both the individual and society, STEM education should be included in the curriculum starting from primary school.
- Schools should encourage students to pursue STEM education and support them in developing their critical thinking and creativity.
- Educators ought to be provided with in-service training on STEM.
- Schools should create special classes and laboratories suitable for STEM education and constructivist approaches.
- Teachers should be careful to keep class sizes small in classes where constructivist methods are applied.

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Chapter 3

STEM and Mathematics: Understanding and Developing Students' Fractions Knowledge through a Radical Constructivist Lens

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Chapter Highlights

This chapter emphasizes the central role of mathematics within STEM education by positioning radical constructivism as a unifying theoretical framework applicable across STEM disciplines. It examines how mathematics education researchers employ radical constructivism to investigate learning processes, with a particular focus on fraction knowledge. Through an illustrative case study on children's understanding of fractions and pedagogical recommendations for supporting older students, the chapter bridges theory, research, and instructional practice.

- STEM and Mathematics – Examining the foundational role of mathematics as a core integrative component of STEM education.
- Radical Constructivism as a Lens for STEM Education – Introducing radical constructivism, contrasting it with the emergent perspective, and discussing its adaptation to classroom contexts.
- Children's Fraction Knowledge – Exploring how children develop an understanding of fractions, supported by an in-depth case study grounded in radical constructivist principles.
- Older Students' Fraction Knowledge – Offering instructional goals and pedagogical strategies to support and extend fraction understanding among older learners.

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Introduction

As you can see in the chapter highlights, this chapter consisting of four subsections: (1) STEM and Math, (2) Radical Constructivism as a Lens for STEM Education, (3) Children's Fraction Knowledge, and (4) Older Students' Fraction Knowledge. Firstly, STEM education has been acknowledged as an essential core for K-12 and beyond as there are many jobs that require knowledge of STEM. Mathematics is a fundamental subject among STEM disciplines. This chapter starts with defining STEM education and the role of mathematics in STEM. Additionally, we suggest fractions as an exemplary topic in this chapter since fractions are used in all STEM disciplines as an essential concept that students need to understand conceptually. We believe this first section provides a broader view of STEM focusing on mathematics for readers.

Secondly, radical constructivism has been used as a framework for all disciplines of STEM. Radical constructivism concerns how a person constructs their knowledge based on their own experiences. In this second section, we explore how radical constructivism view can be applied for classroom context having more complex interaction between a teacher and multiple number of students. To investigate this, we compared emergent perspective to radical constructivism. Since emergent perspective emerged from radical constructivism, we focused on how the emergent perspective is applicable for classroom teaching. We expect this will give insight for teachers about how they can manage classroom discussion in a way that students learn mathematics connecting to their prior experiences or knowledge.

The third section concerns understanding and developing children's fractions knowledge through case-study. The second author of this chapter conducted a teaching experiment with a sixth-grade student to explore his fractions knowledge by posing six fraction problems. Teaching experiment is a methodology coming from radical constructivism aspect by focusing on understanding student thinking. We expect that this case study provides exemplary research to investigate student thinking focusing on a specific content. This approach can be applied for other STEM disciplines when they want to explore student thinking specifically in a topic.

In the final section of this chapter, we discuss older students' fractions knowledge since the topic is challenging for all ages based on the first author's teaching experiences in middle and high school and college teaching. This section suggests for educators to consider reorganization hypothesis, which appreciates students' prior experiences and knowledge of whole numbers to construct new mathematical concepts of fractions. It also provides a brief overview of units coordination and schemes, which can help teachers understand their students' fractions knowledge to support them to develop from individual level of understanding. Finally, this section also suggests the usefulness of visual representation for teaching and learning fractions conceptually. For example, we included pictures that were created by a fraction bar tool, so that instructors can modify from it to apply for their students.

STEM and Math

What is STEM education?

STEM is an acronym for Science, Technology, Engineering, and Mathematics. The term "STEM" was introduced by the National Science Foundation (NSF) in the 1990s. Initially referred to as "SMET" (Science, Mathematics, Engineering, and Technology), the acronym was later changed to "STEM" due to its greater phonetic appeal and ease of use in communication. STEM education integrates four disciplines of science, technology, engineering, and mathematics to promote interdisciplinary learning, with an emphasis on hands-on activities, inquiry-based instruction, and problem-based learning. The goal is to develop students' critical thinking, creativity, and ability to apply knowledge to real-world challenges.

At the higher education level, Virginia Tech University is credited with launching the first graduate-level degree in STEM Education in 2005 to emphasize the educational dimensions of STEM training (Wells, 2013). The program includes core coursework such as EDCI 5804 – STEM Education Foundations, EDCI 5814 – STEM Education Pedagogy, EDCI 5824 – Trends and Issues in STEM Education, and EDCI 5834 – Research in STEM Education. Students may also take electives in areas such as biotechnology literacy (EDCI 5854) and complete field experiences (EDCI 5964) as part of their professional preparation.

In K–12 contexts, STEM education is understood in diverse ways depending on school settings and educator roles. A study identified three common themes across educators' views of STEM education: interdisciplinary connections among science, technology, engineering, and mathematics; the need for new, ambitious instructional practices; and student engagement in real-world problem solving (Holmlund et al., 2018). These shared elements highlight that STEM education involves integrating multiple disciplines through innovative teaching strategies that prepare students to address authentic challenges.

The study also found variation in how STEM education is conceptualized across different educational contexts and roles, suggesting that while a single, universal definition may not be necessary, it is important for educators within the same system to collaboratively develop a clear and common vision of STEM education tailored to their local context. This shared understanding can guide curriculum design, instructional methods, and professional learning to better serve students' STEM learning goals.

Why is math central to STEM education?

Mathematics is widely recognized as the foundational discipline underpinning the other fields within STEM education. Its principles and methods provide the language and tools essential for understanding, analyzing, and solving problems across science, technology, and engineering.

In Science, mathematics is crucial for formulating hypotheses, designing experiments, interpreting data, and modeling natural phenomena. Quantitative reasoning enables scientists to express scientific relationships precisely and predict outcomes (Vera et al., 2021). A study identified prevalent misconceptions regarding mathematical modeling among biomedical experimentalists and suggested practical methods for addressing the cognitive distance between modelers and experimental researchers (Vera et al., 2021).

In Technology, mathematics supports the development and application of algorithms, data structures, and computational methods. From coding software to designing digital systems, mathematical concepts such as logic, discrete math, and statistics play a key role (Liu & Castellana, 2021). Additionally, in Engineering, mathematics provides the framework for designing, analyzing, and optimizing systems and structures (Ramkrishna & Amundson, 2004). Specifically, calculus, geometry, and linear algebra are vital for understanding forces, materials, and processes that engineers work with.

Despite its central role, the importance of mathematics in STEM education is often underestimated (Maass et al., 2019). This underappreciation can lead to insufficient focus on mathematical thinking and skills development, which are essential for success in STEM fields. Therefore, strengthening math education within STEM programs is critical to prepare learners for the interdisciplinary demands of STEM careers.

Why Fractions Matter: Foundational Reasoning for STEM Education

Despite being introduced in elementary school, fractions remain one of the most conceptually challenging topics for students throughout K-12 and even into higher education. Research consistently shows that many students struggle to understand fractions as quantities, instead treating them as disconnected procedures or part-whole representations (cite). For example, Wiest and Amankonah (2019) emphasized that students often confuse the size of a fraction with the size of its components (e.g., thinking 1/5 is larger than ¼ because 5 is larger than 4). Another study pointed out that relying heavily on procedures without conceptual understanding (e.g., cross multiplication with no sense of why it works) (Bansilal & Ubah, 2020). Also, Brown and Quinn (2006) found that students often face difficulties in interpreting improper fractions or mixed numbers. These challenges have long-term implications. Students who do not develop a solid understanding of fractions are more likely to struggle with algebra, proportional reasoning, and advanced mathematical thinking—all of which are foundational to success in STEM fields.

Fractions are not just a school subject—they are critical to reasoning and application across STEM disciplines. Specifically, in science, fractions support reasoning about proportional reasoning, which is foundational concept for concentration or density (Howe et al., 2011). For example, in chemistry, determining the concentration of a solution involves fractional relationship between solute and solvent. In biology, interpreting data such as population growth or decay often depends on fractional changes over time. In physics, concepts like velocity, acceleration, and density are expressed through ratios and fractional quantities. Therefore, without a firm grasp of how fractions operate, students may struggle to reason proportionally, estimate accurately, or interpret scientific data.

Engineering applications often relies on scaling and measurement, which require reasoning with fractions (Bird, 2014). For example, reading blueprints or creating scaled-down models of buildings or machines demands accurate fractional understanding. Moreover, material tolerances are often expressed as small fractional margines (e.g., 1/8 of an inch). Structural load distribution and energy efficiency calculations also involve fractional reasoning. Hence, lack of fractions knowledge might hinder students' capacity to engage in authentic engineering design or phototyping.

In technology fields, fractions are embedded in both conceptual and computational tasks (Fang et al., 2023). For instance, time-based media, such as editing audio or video, require fractional divisions of seconds (Herglotz et al., 2020). Also, data visualization often involves interpreting fractions, such as pie charts or percentages of user engagement. Especially in computer science, data encoding may involve fractional bases (Fang et al., 2023). Understanding fractions enables more efficient data manipulation and improved digital literacy.

Furthermore, fractions are fundamental to mathematical modeling, which is at the core of STEM problem-solving (Wilkins & Norton, 2018). For example, modeling with mathematics often involves fractional quantities, especially in real-world problems. Additionally, algebraic reasoning depends on students' comfort with variables and operations involving fractions (Hackenberg, 2013)2013. Thus, students' robust conceptual understanding of fractions plays a crucial role in access to STEM coursework.

Radical Constructivism as a Lense for STEM Education

von Glasersfeld's (1995) radical constructivism serves as the underlying theory of learning. Rooted in Piaget's constructivism, radical constructivism holds that each student creates their understanding of the world based on prior experiences and interactions with the environment—which includes interactions with other people. Therefore, the teacher's role is guiding children to connect from their prior experiences to a new concept.

Emergent Perspective Takes from Radical Constructivism

First, the Emergent Perspective "follows Glasersfeld (1992) in using the term *knowledge* in 'Piaget's adaptational sense to refer to sensory-motor and conceptual operations that have proved viable in the knower's experience'" (Cobb, 2000, p. 154). Concepts of truth, viability, assimilation, accommodation, instrumentalism of knowledge, intersubjectivity, and reflective abstraction are also brought from Radical Constructivism. Similarly, communication between individuals is not seen as an exchange of fixed meanings. While communicating, to understand what other person has written or said, implies "to have built up a conceptual structure from an exchange of language, and, in the given context, this structure is deemed to be compatible with what the speaker appears to have had in mind(von Glasersfeld, 1995, p. 143).

In both perspectives, communication involves a process of negotiation of meaning, and interaction with others is conceived as an important source of perturbations. From Cobb's point of view, von Glasersfeld does not only conceive that learning is stimulated by social interactions, but he conceives it as being social (Cobb, 2000). Therefore, both the Constructivist and Emergent Perspective consider learning as self-organization, socially, and culturally situated.

Differences between the Emergent Perspective and Radical Constructivism

The divergence from Radical Constructivism started in 1986 (Cobb & Yackel, 1996). At the time, the authors were conducting *Developmental Research*, which they characterize as involving hand in hand, instructional development and classroom-based research. They initially used Radical Constructivism to interpret and discuss the students' mathematical conceptions, activity, beliefs, and learning in individualistic psychological terms. However, they concluded that such accounts were "inadequate" for the purposes of their developmental research study (p.176). As we interpret it, the individual accounts were inadequate in the sense that they were insufficient for describing the "students' mathematical development *as it occurs in the social context of the classroom"* (p.176).

That is, the result they obtained did not adequately account for the student's development in relation to what was happening at the level of the classroom micro-culture. Therefore, the divergence from radical constructivism was pushed forward by an experienced need to explore further the students' mathematical development in the social context of the classroom. This mathematical development is ultimately accounted for through the constructs: Classroom Social Norms, Socio-Mathematical Norms, and Classroom Practices.

From our interpretation, the central difference between one perspective and the other is that while Radical Constructivism focuses in the "individuals' construction of their ways of knowing" (Cobb, 2000, p. 155), the Emergent Perspective does not conceive of accounting for individual student's mathematical reasoning without accounting for the development of the classroom microculture. As they put it, they question "the assumption that such analyses [i.e., psychological constructivist analyses] can, in principle, capture individual students' conceptual understandings independently of situation and purpose" (p.185).

Instead, "individual student's mathematical activity and the classroom microculture are reflexively related (Cobb, 2000, p. 155). The relationship is deemed to be *reflexive* in the sense that the involved aspects are interdependent, but neither can be adequately accounted for without considering the other. The individual thinking of the students contributes to the evolution of the classroom norms and practices, and the classroom norms and practices open and close down possibilities for students' learning. That is, both enable and constrain each other.

We previously mentioned that both perspectives conceive of social interaction as a rich source of perturbations and consequently, the result can be mathematical learning and development. Nevertheless, from Emergent Perspective's point of view, social interaction serves as more than just a *catalyst* of individual development. "Learning is not merely social in the sense that interactions with others serve as a catalyst for otherwise autonomous conceptual development. Instead, the products of learning, increasingly sophisticated ways of knowing, are also social through and through" (Cobb, 2000, p.154).

To close this section on differences between the two perspectives, we will make one last point. Studying classroom events by using the Emergent Perspective might involve similar processes as those proposed by Steffe and Thompson's (2000) constructivist teaching experiment (e.g., interviews, teaching episodes, on-going and retrospective analysis). Both intend to account for the students' individual reasoning and how they modify their mathematical activity.

One clear difference is that teaching experiments are usually conducted with one or a couple of students, whereas the Emergent Perspective is a framework that supports the interpretation of events either between a couple of students or during a full classroom lesson. Furthermore, besides accounting for individual learning, Emergent Perspective intends to parallelly account also for the mathematical development at the level of the social context of the classroom. In order to make these accounts is that Cobb and Yackel turned to Interactional Theory.

Using Interactional Theory to Account for the Students' Mathematical Development as it Occurs in the Social Context of the Classroom

As mentioned before, the Interactionist complement that constitutes the Emergent Perspective is mainly taken from Bauersfeld et al. (1988), work that was developed in light of Blumer's (1969) Symbolic Interactionism and Mehan and Wood's (1975) ethnomethodology. Blumer (1969) asserts that Symbolic Interactionism corresponds to a particular "approach to the study of human group life and human conduct" (p.1). He explains that there are two levels of social interaction: *conversation gestures* and the *use of significant symbols* which correspond respectively with *non-symbolic interaction* and *symbolic interaction*. The difference between one and the other is that the second one involves an interpretation of action. While non-symbolic interaction is more evident, (e.g., in reflex responses), symbolic interactions require that the participants make an unobservable interpretation of each other's actions and utterances.

The interaction between a group of people consists of the fitting of the different participants' *lines of action*. This articulation gives way to a *joint action* that is not considered as the mere aggregation of each of the lines, and it is thought to be different from each of them. This joint action undergoes a process of formation and Blumer (1969) asserts that "even though it may be a well-stablished and repetitive form of social action, each instance of it has to be formed a new" (p.17).

Analogously, when referring to interactions in the context of a classroom, Cobb and Bauersfeld (1995) express that a "linguistic processes can be viewed as an accomplishment of language games that are special to each classroom, and in which the teacher and students negotiate *taken-as-shared* meanings and signs" (p.13). The expression 'taken-as-shared' is used to indicate that "individual interpretations fit for the purposes at hand but does not imply that they necessarily match" (Cobb, 1996, p.166).

In a math classroom, the interaction that occurs generates a negotiation of meaning in which each of the participants (i.e., the teacher and students), make adaptations and mutually establish expectations of each other. As these implicit negotiations take place, "teachers and students are seen to jointly constitute *classroom norms and practices* in the course of their interactions" (Cobb, 1996, p. 155). The norms and practices can be said to *emerge* from the interactions that occur among participants in the specific classroom context, which points particularly to the idea of "emergence" in the framework. Classroom practices are not considered to exist prior and independently from the teacher and student's activity; practices emerge through interactions of the teacher and the students.

In sum, Cobb and Yackel referred to Interactional Theory for developing the Emergent Perspective due to their shared view that "learning and understanding are inherently social and cultural activities" (Cobb & Yackel, 1996, p185). That is, student learning and understanding cannot be accounted for without also accounting for the development of the classroom microculture. Note that although the Emergent Perspective shares many key assumptions and constructs with the Interactional Theory, Cobb and Yackel (1996) also point out some central differences between the Emergent Perspective and Socio-cultural Perspectives in general. Some of those differences include whereas the first focuses on a local community (i.e., a classroom microculture), the latter typically views individuals as participating in broader socio-cultural practices. Furthermore, while Socio-Cultural perspectives are often framed using conceptualizations such as negotiation as "mutual appropriation" and instructional issues as "transmission of culture"; the Emergent Perspective conceives negotiation as "mutual adaptation" and instructional issues in terms of "emergence" (Cobb & Yackel, 1996, p.186).

A Closer Look at Using the Emergent Perspective in the Context of Developmental Research

Now that the general ideas of the Emergent Perspective have been presented, we will provide more detail about the use of this perspective in the context of research. As mentioned above, the Emergent Perspective arose from a series of studies that involved *Developmental Research*. According to Cobb (1996), classroom analyses that are conducted through developmental research should fulfill three criteria: (a) They should emphasize not only the mathematical development of the classroom community, but also of the individual students. (b) The constant analysis performed should provide feedback with regards to the continuing process of instructional development. (c) The mathematical learning of the classroom community and the individual students should be documented in a detailed and meticulous way over extended periods of time.

In understanding what developmental research entails, we also find significant the way Gravemeijer (1994) describes it. That is, by citing Freudenthal, who in 1991 wrote that Developmental Research involves "experiencing the cyclic process of development and research so consciously, and reporting on it so candidly that it justifies itself, and that this experience can be transmitted to others to become like their own experience" (p. 452).

Cobb, Yackel and Wood (1992) further explain that Developmental Research requires a cyclical combination in which a *Development Aspect* is guided by discipline-specific instructional theory, and a *Research Aspect* is guided by an interpretative framework. On one hand, the *Developmental Aspect* alludes to classroom-based research used towards generating instructional development. Existing literature is used to construct a sequence of instructional activities, which should envision how the teaching process and student's mathematical learning might proceed. Envisioning such a complex process involves formulating "conjectures about both student's possible learning trajectories, and the specific means of supporting, organizing and guiding that development" (Cobb, 1996, p.157).

Once a first version of the sequence of instructional activities is completed, its enactment is a necessary and important step. As Gravemeijer (1994) mentions, "what is invented behind the desk is immediately put into practice; [furthermore], what happens in the classroom is consequently analyzed, and the result of this analysis is used to continue the developmental work" (p. 449). In analyzing what is put into practice, the research team must analyze whether the activity proceeded as initially envisioned. Particularly by testing the formulated conjectures.

Besides enacting one or more instructional activities from the sequence in a classroom context, further insightful data can be generated from individual interactions with the students (e.g., interviews). The feedback obtained from the collected data allows researchers to reformulate their hypotheses and expectations, leading to modifying the instructional sequence, which should be put into practice and analyzed. In this sense the study undergoes a cyclical process that involves redesigning the instructional sequence and interpreting its implementation. Each of the iterations of the cycle involves constant reflections on the theoretical foundations and the empirical data produced. The cycle may act on different levels, between class sessions or between periods of time in which the research is being done.

On the other hand, the *Research Aspect* (i.e., interpretive framework) provides a set of assumptions, principles, and practices for the process of interpretating the generated data. Cobb and Yackel propose to use The Emergent Perspective to be such interpretive framework. In order to operationalize the framework in a way that makes its use accessible, Cobb and Yackel define *aspects* to account for from the psychological perspective and aspects to account for from the interactional perspective. Let's explore these aspects a little further.

Aspects of Classroom Micro-Culture and its Psychological Correlates

Providing rich and significant reports about both the classroom and individual development is no doubt a demanding but also insightful task.

To emphasize both kinds of development, the Emergent Perspective considers three main aspects of classroom microculture accompanied by three psychological *correlates* (see Table 1). The word correlate, as used in this perspective, alludes to a relation of complementarity, "a conjectured relation between an aspect of the classroom microculture and the activity of the individuals who participate and contribute to it." (Cobb & Yackel, 1996, p. 177).

Table 1. Aspects of classroom microculture and the psychological correlates considered in the Emergent Perspective as interpretive framework.

Aspects of classroom microculture	Individual aspects
Classroom social norms	Beliefs about own role, other's roles, and the general nature of mathematical activity in school
Socio-mathematical norms	Mathematical beliefs and values
Classroom mathematical practices	Mathematical conceptions and activity

As mentioned before, classroom microculture and individual mathematical activity maintain a reflexive relation; therefore, the three pairs of corresponding aspects are also reflexively related. Neither of them is seen as being the cause of the other, and neither is claimed to come first. That is, for example, in the case of the first pair, individual beliefs contribute to the evolution of classroom norms and simultaneously, the renegotiation of social norms in the classroom supports the student's reorganization of their beliefs. Although this reflexive relation is constantly emphasized in the articles, Cobb (1996) also expresses that they regard it as a conjecture open to empirical investigation.

The Three Psychological Aspects. Let's address first the issue of how to account for the students' individual progress. One thing that we have noticed is that in many different articles about the Emergent Perspective, not much is being said about the individual part of the analysis. We infer that this is because publications such as Cobb and Steffe (1983) and Steffe and Thompson (2000), among others, portrait rich explanations on how to carry out this type of process. That is, they usually include conducting individual (or with a small number of students) teaching experiments and interviews.

Nevertheless, our understanding is that what has been brought intact from constructivist teaching experiments is the use of interviews. As suggested before, part of the data related to the evolution of the students' mathematical understanding and learning during the period of research, is obtained through a sequence of individual interviews. In these interviews, the main interest is to understand the students' reasoning, describe the changes in their procedures and strategies, and identify and explain the progress they have achieved.

We interpret that some other data to account for individual learning can also be obtained from the students' individual participation and contributions to the classroom discussions. From the examples provided in Cobb (1996), we also infer that an important part in accounting for individual learning is being aware of the different achievements of the students in comparison to other students or groups of students. Supporting evidence for this interpretation is the following description that Cobb (1996) uses when exemplifying individual progress:

"In contrast to the September interviews, ten of the eighteen students used non-counting thinking strategy solutions to solve all the tasks posed to them in interviews conducted in January... A further three students used to think strategies to solve at least half of the tasks presented, and the remaining five produces relatively sophisticated counting solutions." (p159)

From our point of view, the two other individual psychological aspects (i.e., beliefs about the students own role, the role of others and the nature of mathematical activity in school; as well as the mathematical beliefs and values), do not seem to have a primarily role in the descriptions and explanations presented as result of the research. What seems to be mostly documented is the communal organization of their beliefs, that is, the classroom mathematical practices and the socio-mathematical practices.

The Three Aspects of Classroom Micro-Culture. With regards to the three aspects of the classroom microculture, the collection and analysis of data resembles Steffe and Thompson's (2000) teaching experiments but transported to the classroom context. In this sense Cobb and Yackel (1996) refer to the process as constituting a *Classroom Teaching Experiment*. As previously indicated, central aspects to focus on when studying the development of the classroom community are social norms, socio-mathematical norms, and classroom mathematical practices. From our point of view, most of the articles about the Emergent Perspective dedicate a lot of more detail on these three social aspects because they constitute novel elements proposed by in the Emergent Perspective, in comparison to other interpretive frameworks. Let's explore each of these three aspects.

Classroom social norms. Cobb and Yackel (1996) note that when inquiring into a student's autonomous learning and development, one would need to account for their beliefs about their own role, others' roles and the general nature of mathematical activity in the school (i.e., the first individual aspect from table 1). The social correlation is classroom social norms, which primarily delineate classroom participation structure Cobb (1996).

From a general definition by the Merriam-Webster Dictionary (https://www.merriam- webster.com), a norm can be understood as "a principle of right action binding upon the members of a group and serving to guide, control, or regulate proper and acceptable behavior", and "a pattern or trait taken to be typical in the behavior of a social group". More specifically, Cobb and Yackel (1996) state that Classroom Social Norms "are not psychological processes or entities that can be attributed to any individual. Instead, they characterize regularities in communal or collective classroom activity and are jointly established by the teacher and students…" (p. 178).

Examples of these norms are the commitments that the students make within the classroom context, such as sharing and justifying their reasoning, listening and trying to understand their classmates' ideas, and being able to comment on them. Primarily therefore, Classroom Social Norms refer to acts of explanation, justification, and argumentation (Yackel & Cobb, 1996).

A particular case in which the first stages of emergence of social norms can be evidenced, is when a teacher starts to work with a new group of students. It is possible that the teacher's expectations about behavior and participation are different from the students' expectations and prior experiences (Cobb & Yackel, 1996). Consequently, a process of renegotiation of classroom social norms would be initiated. It is important to note that although the teacher is in charge of initiating, guiding and organizing the renegotiation process, the students also contribute to the evolution of the norms. Conversely, as the students interpret and make sense of the different contributions, they also reorganize their beliefs about the roles within a classroom.

A final point to make is that classroom social norms can also be found in classrooms from other subjects. Explanation, justification, and argumentation could easily be present outside of mathematics classrooms. Consequently, Cobb and Yackel found themselves with the need to differentiate these norms from those that involve mathematical elements. For this reason, another useful construct that constitutes the Emergent Perspective is the socio-mathematical norms.

Socio-Mathematical Norms. These are "normative features of students mathematical activity"; that is primarily, norms of what counts as acceptable, different, or insightful mathematical solutions (Cobb, 1996, p. 161). The students with the teacher, through their discussion and interaction in class, decide whether a strategy is valid, if it is different from another already discussed, or if it is more sophisticated or desirable for the class. Cobb also explains that these norms evolve through time within a classroom, which strengthens the claim that mathematical norms can be very different from one classroom to another.

In developing this type of norm, it seems that initially the students might not be sure of what counts as acceptable, different, or more sophisticated answers. Not only the feedback, reactions and comments of the teacher help to the formation and evolution of the norm, but also the students' ideas and contributions. This is particularly evident for example, when the teacher instead of defining in advance a strictly unchangeable script of what will count as acceptable, different, or sophisticated; is open to make these decisions as a classroom community in the course of the interaction. The negotiation of socio-mathematical norms in this way is thought to allow the students to improve their mathematical reasoning and argumentation and avoid being limited to following a prescription from the teacher or the book.

Let us explore a little more what entails establishing norms regarding acceptable, different, and insightful mathematical solutions. First, in a discussion for deciding whether a solution is acceptable or valid, the students would have to share their strategies and procedures, while the rest of the class would have to interpret them. As the class reacts to the solutions and explanations, either with compliments, questions or objections, the classroom community negotiates what counts as an acceptable solution and what does not.

Second, establishing mathematical norms about similarities and differences is particularly stimulated when the teacher asks if anyone has solved the problem in a different way. Solutions could be judged to be different, for example, if they involved different calculational processes or different quantitative interpretations. These socio-mathematical norms emerge from the class discussion, and in Cobb and Yackel's (1996) classroom experiments, sometimes the judgement of the class was different from the judgment they, as researchers, made. The practice of comparing provides an opportunity for the students to advance into higher-level cognitive activity.

Last, to decide whether an answer is more sophisticated or insightful than others, one essential element is the way the teacher responds to them. The physical reaction that the teacher has as well as expressions such as “yeah!” “I like that” “listen to her/him!” “that’s good!” provide elements that the classroom community uses to learn about what counts as “conceptually advanced forms of mathematical activity” (Yackel & Cobb, 1996, p. 465). These types of judgements are less evident in comparison to the previous two, since it is usually not explicitly discussed whether an answer was more satisfying or efficient than another, and “the children are left to decide in what sense the solution was special” (Yackel & Cobb, 1996, p. 464).

Cobb and Yackel (1996) indicate that a characteristic that should be met by socio-mathematical norms is that they result from mathematically productive discussions, which requires for the students to have developed “personal ways of judging.” (p. 179). During the negotiation of socio-mathematical norms, the students should not only explain and make arguments for their ideas but also take the explanations as objects of reflection. They must make their explanations not only valid for themselves, but also understandable for their classmates.

There will always exist individual differences and achievements from one student to another. It is part of the teacher’s role to be aware of the individual advances of his/her students and to accept and value different types of answers based on that. The teacher plays a very challenging role, since she or he is in charge of legitimizing the students contributions and also, “it is the teacher’s responsibility to make judgments about the extent to which students take something as shared and to facilitate communication by explicating the need for further explanation” (Yackel & Cobb, 1996, p.471).

When reflecting about social norms and mathematical norms, it is possible to find oneself with many questions about what counts as a norm and what does not. For example, if a classroom social norm is that all the students should try to understand their peers’ ideas, does that mean that all the students do understand all of their peers’ ideas all the time? We would say that the answer is no. A reason why trying to understand other students’ ideas might count as a norm could be its quality of happening regularly.

A more complex question could be, how can one determine regularity? Or, what if some students act according to the norm, but other students do not at all? Although we have found explicit reference to questions of this type. The establishment of a norm is highly context- dependent, reason for which, we infer, it is not possible to offer an exact set of parameters that define what counts and does not count as a norm. We further infer that a norm is a taken-as-shared understanding of what is expected and possibly encouraged in the classroom micro-culture. That is, a student might not always act according to a specific norm, and still consider it as something that is expected from him/her to engage in.

One last key question that might arise could be related to the boundary line between classroom social norms and socio-mathematical norms. We personally think that a good way to differentiate between one and the other is thinking that the first type of norm leans towards ways of participation in the class (e.g., explaining procedures, judging, and classifying strategies). The second type of norm, on the other hand, refers to the products of the reflections and discussions that occur in the classroom. An example of a socio-mathematical norm could be, when subtracting 11-7, conceiving (a) subtracting seven from ten and adding one, as more sophisticated than (b) counting forward from seven to eleven. The act of discussing and judging if they are valid or different, is a classroom social norm; but the taken-as-shared agreement that the type of strategy (a) is more sophisticated than the type (b), is a socio-mathematical norm.

Classroom Mathematical Practices. The third and last element to account for when studying the development of a classroom community is the Classroom Mathematical Practices. It is important to note that the psychological correlative of this aspect is the student's mathematical conceptions. In a constructivist teaching experiment, as described by Cobb and Steffe (1983), one of the goals is to identify and explain patterns and evolution of the students' reasoning. The Classroom Mathematical Practices also support tracing the mathematical development and the evolution of the student's procedures and reasoning as they become more sophisticated. The difference is that the practices concern procedures and reasoning of the classroom community as a whole. In Cobb (1996) and Cobb and Yackel (1996), the classroom mathematical practices are described as practices that become routine, practices that do not need justification, and interpretations that are *taken as shared* by the teacher and the students. To understand better what it is referred to when saying that a practice becomes routine, suppose that a student proposes a novel, appealing, or effective new way of solving a specific kind of problem. At the beginning, the classroom community might have an active discussion about the acceptance and qualities of this practice. The students that propose the practice might need to provide clear justifications for its acceptance. Eventually, the classroom community might continue to use the practice, until it becomes a common routine, and does not need further justification. What started as a novel way of solving a problem would become classroom mathematical practice.

Not that it is not assumed that an accepted practice is one that is understood in the same way by everyone in the classroom community. The *taken as shared* interpretations and practices are said to be established as opposed to *shared* interpretations and practices. A taken as shared interpretation of the practice entails attaining intersubjectivity (cf. Von Glasersfeld, 1995), in the sense that there are no apparent disagreements present.

Cobb (1996) explains that these practices generally evolve and change over time. As an example, consider the following evolution of a classroom mathematical practice for adding a group of six candies to a group of four candies. At first, the class could have as a routine to start counting all the first six candies (i.e., one, two, three…, six) and then continue counting (i.e., seven, eight, nine, ten) until finding the answer. Later on, the class could migrate to start from six and count forward (i.e., seven, eight, nine, ten) to find the answer. Eventually, the class could agree to use more sophisticated strategies such as transferring one candy from the second group to the first one, obtaining five plus five and a more immediate response of ten. It is worth saying that this example was not taken from a documented real experience, but it is a product of our personal understanding of what counts as an example of mathematical practices.

Similar to what We exposed for the norms; one can encounter several key questions when reflecting about mathematical practices. For example, in the candy example, transferring a candy from one group to the other is a significantly more advanced way of solving the problem than counting the first six candies and then continuing counting. In a classroom, there could be students at different stages in their numerical development. If some students can easily conceive transferring a candy from one group to the other, but other students do not yet reason in this way, can the transferring strategy be conceived as a classroom mathematical practice?

Although we did not find an explicit response to questions like this, we infer that the response is yes. We infer that establishing a mathematical practice does not necessarily mean that every single student in the classroom necessarily engages in the practice. From our interpretation of both Cobb (1996) and Cobb and Yackel (1996), we understand that it is possible that multiple practices are enacted at the same time, depending on the individual development and preferences of the students. That is, in the context of the candy problem, it is possible that some students use the transferring strategy, whereas other students remain using the counting from six strategy. Both practices considered established and accepted within the classroom community. Furthermore, for the latter students, the transferring strategy could represent a practice to work towards.

Another aspect to point out is that a potential shift from one practice to another might occur over a period of several weeks. Although the students contribute to the emergence of the practice, the teacher, as leader in the classroom, takes an important part in pursuing the establishment of a particular practice. Usually, mathematical practices emerge from explicit negotiations facilitated by the teacher. This brings forth connections between the mathematical practices and the learning goals that the teacher determines for the lesson or unit. In this sense, Cobb and Yackel (1996) point out the relevance of mathematical practices towards documenting instructional sequences that take place in classroom interaction, as well as documenting the social situations in which students participate and learn. Ultimately, portraying the process of the mathematical development of the classroom community.

Cobb and Yackel (1996) stress the clarification that making accounts of the mathematical development of the classroom as a community does not deny or ignore the student's individual differences. It is the goal of the psychological analysis aspect of the Emergent Perspective (i.e., individual aspects shown in table 1), to "reveal qualitative differences in individual children's mathematical interpretations even as they participate in the same mathematical practices" (p.180). At the end of successful developmental research using the Emergent Perspective, the researchers should be able to differentiate students from different classrooms, and they should also be able to identify differences between groups of students and individual students within a classroom. This would be a manifestation of having accounted for both classroom micro-culture and individual development.

A Case Study of Understanding and Developing Children's Fractions Knowledge

For much of the history of mathematics education, the subject has often been treated as a fixed body of unquestionable rules and procedures to be mastered through repetition and memorization. This traditional view positioned learning as the accumulation of established facts rather than as an active process of meaning-making. In recent decades, however, mathematics education has undergone significant change, influenced by scholars and educators who view mathematics through multiple perspectives. Questions such as "How can mathematics be taught most effectively?" and "How can we engage children's genuine interest in mathematics?" have driven efforts to renew both theory and practice (Nelissen, 1999). As part of this evolution, earlier learning theories have been refined, and new ones have emerged.

One of the most influential is constructivist learning theory, often described as a "learner-centered" or "interest" theory. In mathematics education, constructivism emphasizes that children actively build mental representations images, diagrams, methods, intuitions, and thought processes in response to mathematical ideas. Teaching mathematics through constructivist activities means valuing these representations and the discoveries children make, positioning the learner's thinking at the center of instruction.

The belief that learning is an active process undertaken by the learner, rather than the passive reception of knowledge, can be traced to philosophers such as Socrates and Kant (von Glasersfeld, 1991). In education, constructivism's most significant development came through the work of Jean Piaget (1896–1980), founder of cognitive psychology, whose research shaped contemporary understandings of how knowledge is formed (von Glasersfeld, 1991).

In Turkey's national curriculum, the constructivist approach has been adopted as a guiding principle for mathematics education. Teachers are expected to use student-centered techniques, strategies, and methods that allow learners to discover and make sense of concepts independently. Teacher training programs and school curricula are aligned with this philosophy.

The present study had two main aims: (1) to understand the fraction knowledge of a child taught under a constructivist-oriented curriculum, and (2) to develop the child's knowledge of multiplying fractions, a topic he/she had not yet formally studied.

Background on Fraction Learning Challenges

Fractions have long been a central yet challenging topic in mathematics education. Many students struggle with fractions well into secondary and even post-secondary education. In some cases, proficiency with fractions is considered a predictor of broader mathematical success (Kerslake, 1986). Yet fraction instruction often induces anxiety, sometimes as a result of overly procedural teaching. When fractions are taught only as a set of rules—such as "With the same numerator, the fraction with the smaller denominator is greater" or "When dividing by a fraction, invert and multiply" students may fail to understand the concepts underlying those rules. As a result, they often misapply procedures and struggle to connect fractions with their natural number knowledge.

Theoretical Framework

This case study draws primarily on Steffe and Olive (2010) as a reference for understanding children's fraction knowledge. A central hypothesis in their work is that fraction knowledge develops in harmony with, and is constrained by, a child's existing whole number understanding. Rather than relying solely on adult or formal mathematical structures to interpret a child's thinking, Steffe and Olive focus on what children themselves can construct as mathematics.

To examine fraction knowledge, it is important to distinguish between first-order and second-order mathematical knowledge (Cobb & Steffe, 2011): First-order mathematical knowledge refers to the mental models and structures an individual constructs to organize and make sense of their own experiences. Second-order mathematical knowledge refers to the models that an observer (such as a researcher or teacher) constructs to describe and interpret another person's mathematical understanding.

Steffe and Olive (2010) were primarily concerned with second-order knowledge, arguing that to assess children's mathematical understanding accurately, educators must focus on the child's own mathematics not merely on adult interpretations of it. They use the terms: "Children's mathematics" as whatever constitutes a child's first-order mathematical knowledge, "Mathematics of children" as second-order models of children's mathematics, and "Mathematics for children" as concepts and operations that children are ready to learn, based on their current understanding. In building "mathematics for children," understanding both children's mathematics and the mathematics of children serves as the foundation for instructional design.

Number Sequence Development

Research on children's number sequences further informs this study. From teaching experiments, Steffe and colleagues identified three developmental stages: (1) Initial Number Sequence (INS) internalization of basic counting activity, (2) Tacitly Nested Number Sequence (TNS) recognition of parts within a whole without explicit coordination, and (3) Explicitly Nested Number Sequence (ENS) explicit coordination of nested units within a whole.

Each new sequence is built upon the restructuring of the previous one, and gaps in this progression can hinder later learning. For example, a child lacking fluency with whole numbers may also struggle to develop robust fraction concepts. Conversely, mastery at one stage supports readiness for the next. In this study, the student had progressed beyond ENS to the Generalized Number Sequence (GNS) stage, enabling efficient whole-number operations but still showing difficulty linking those skills to fraction reasoning.

Methodology

The study involved interviews with a sixth-grade student, "Bernard," using six fraction problems (Table 2). The first four questions probed his existing fraction knowledge; the last two were presented after instructional sessions on multiplying fractions. Data were collected via Zoom, with both video and written work recorded.

During each task, the teacher used the Fractions Bars software to mirror and clarify the student's representations. The instructional sequence incorporated three lessons from a Turkish Ministry of Education-approved textbook, supplemented with explanations addressing misconceptions revealed in the first four problems. Notably, Bernard reported that his school lessons did not use computer-based tools, instead relying on a locally published textbook.

Table 2. Focus and Tasks for Data Collection

Focus	Task
Student's prerequisite knowledge of fractions	Q1. Enes divides the first stick in his hand into 4 pieces and takes one for himself. Then he divides the second rod of the same length into 5 parts and takes one for himself. Which piece is longer?
	Q2. Bekir divides a stick in his hand into 5 equal parts and paints them blue. Then he divides another stick of the same length into 5 equal parts and paints three of them green.
	Q3. Bekir divides a stick into 4 equal parts and paints 3 of them blue. Then he divides another stick of the same length into 7 equal parts and paints 5 of them green. Which one is longer? The total length of the green bars or blue bars?
	Q4. We have two rectangular cakes of equal size. How would you share these two cakes equally among 3 people named Bekir, Enes, and Ashly? What is the ratio of the cake would Bekir get and one cake? What is the ratio of the cake would Enes get and two cakes?
Researcher-led teaching fraction multiplication	Q5. Bekir reserved 1/3 of the cake for himself. Later, he divided the cake he had allocated for herself into 7 equal parts and took 1 portion for himself. In the last case, what is the ratio of the cake Bekir allocated for himself to the whole cake?
	Q6. Enes answers (5/6) five-sixths of the questions in the exam. Since (2/3) two-thirds of the questions answered by Enes are correct, what is the ratio of the questions Enes answered correctly to all questions?

Analysis and Protocols

To assess Bernard's prior understanding of fractions, we analyzed data from the first four interview tasks. Each problem explored a different aspect of fraction comparison, representation, and reasoning. Because Bernard had been educated entirely in Turkey and spoke only Turkish, all interviews were conducted in Turkish and later translated into English by the author. The names in the problems were chosen from familiar Turkish names to help him visualize the scenarios more easily. This strategy, informed by our earlier teaching experience, helped reduce student anxiety and bias toward word problems.

A recurring challenge for many learners is that fear of mathematics can create a barrier to performance. Building a safe and supportive learning environment where students feel comfortable making mistakes is critical to helping them engage fully with mathematical ideas.

Protocol 1 – Comparing Different Partitions of Equal Wholes

Task: Enes divides the first stick into 4 equal pieces and keeps one. He then divides a second stick of the same length into 5 equal pieces and keeps one. Which piece is longer?

Student's Work and Dialogue:

Bernard first drew the two sticks. He divided the first into four equal parts and the second into what he initially thought were also four parts. Upon correction, he redrew the second stick into five equal parts.

Researcher: Which piece is longer?
Bernard: The first piece.
Researcher: Why?
Bernard: It's 1/4. (pause)
Researcher: And the second piece?
Bernard: Five over one… oh, no—it's 1/5.
Researcher: Why is the first longer?
Bernard: Because the square made by 1/4 is larger than the one made by 1/5.

Interpretation:

This task assessed understanding of how partitioning affects unit size. Bernard confidently identified the longer piece and explained the relationship between denominator size and part size. His reasoning demonstrated that, for equal numerators, a larger denominator produces a smaller fraction. Although the task was relatively simple for his grade level, it set the stage for more complex comparisons in subsequent protocols.

Protocol 2. Comparing Fractions with Equal Denominators

Task: Bekir divides one stick into 5 equal parts and paints two parts blue. He divides another stick of the same length into 5 equal parts and paints three parts green. Which total is longer: the green parts or the blue parts?

Student's Work and Dialogue:

Bernard drew both sticks, dividing each into five parts. He colored two parts of the first stick blue and three parts of the second stick green.

Bernard: Green is longer, but blue is bigger.
Researcher: How is that?
Bernard: There are 3 green parts and 2 blue parts… but… 2 is bigger

because 3 remain yellow.

Researcher: Let's write them as fractions. Blue?

Bernard: 2/5.

Researcher: Green?

Bernard: 3/5.

Researcher: Which is longer?

Bernard: (pause) 3/5. Greens are longer.

Interpretation:

Initially, Bernard confused the total number of colored parts with the size of the parts themselves, suggesting a momentary mix of quantitative and qualitative reasoning. Once the fractions were expressed numerically, he correctly concluded that 3/5 is longer than 2/5. His success here, as in Protocol 1, indicated secure understanding of comparisons when denominators are equal.

Figure 1. Bernard's Picture and Teacher's Picture

Protocol 3. Comparing Fractions with Different Denominators

Task: Bekir divides one stick into 4 equal parts and paints 3 parts blue. He divides another stick of the same length into 7 equal parts and paints 5 parts green. Which is longer: the total green length or the total blue length?

Student's Work and Dialogue:

Bernard drew the first stick in the fourth, coloring three parts blue, and the second stick in sevenths, coloring five parts green.

Researcher: Fractions for each?

Bernard: Blues are 3/4, greens are 5/7.

Researcher: Which is longer?

Bernard: 5/7—because the numbers are bigger.

Researcher: What if we look at them side by side?

Bernard: Oh… 3/4 is longer.

Researcher: Do you remember what to do when comparing fractions with different denominators?

Bernard: I don't remember.

Bernard's first response relied on comparing numerators and denominators in isolation rather than in relation. His visual model was also inaccurate, the two drawn sticks were not the same length, making the comparison harder. When presented with an accurate visual model in the Fractions Bars program, he recognized the correct answer. The exchange revealed gaps in his procedural knowledge for comparing fractions with unlike denominators, suggesting that he had either not fully learned or had forgotten how to find common denominators.

Protocol 4. Partitioning Multiple Wholes Equally

Task:Two rectangular cakes of equal size must be shared equally among three people: Bekir, Enes, and Ashly.

What fraction of one cake does Bekir get?
What fraction of two cakes does Enes get?
Student's Work and Dialogue:

Bernard drew two identical rectangles, each divided into three equal parts. He assigned two parts from each cake to each person.

Researcher: How many pieces does each person get?
Bernard: Two pieces. That's 2/3. Everyone gets 2/3.
Researcher: So Bekir gets what fraction of one cake?
Bernard: 2/3.
Researcher: And Enes from two cakes?
Bernard: 1/3—because he gets 1/3 of each cake.

This problem assessed his ability to coordinate multiple wholes in an equal-sharing context. Bernard's correct and confident reasoning suggested he could operate at a level corresponding to at least Stage 3 of Hackenberg's fractions framework, managing composite units across multiple wholes without difficulty. In the next stage, the lessons are made with Bernard and as a result of these lessons, the development of Bernard on multiplying fractions will be examined. Our reference source for lecturing has been the (Hackenberg et al., 2016) book, and the examples in this book were used during the lecture.

Developing Children's Fraction Knowledge

As a teacher with prior experience working mainly with high school students, we had limited experience teaching middle school learners. Before working with Bernard, we watched numerous instructional videos from online course platforms commonly used by students. We also drew on examples from Developing Fractions Knowledge (Chapter 10) by Hackenberg et al. (2016) to inform our lessons. One observation stood out: many online platforms focus almost exclusively on teaching rules when introducing fractions. In these lessons, the emphasis is on memorizing a procedure rather than allowing students to discover it for themselves a clear departure from the constructivist approach. Almost all teachers began with statements such as, "When you multiply fractions, first multiply the numerators, then multiply the denominators, and write the result as a fraction."

This teacher-centered approach raises questions about how truly student-centered such instruction can be. In contrast, the mathematics textbook recommended by the Turkish Ministry of National Education employs more student-centered methods, such as the modeling method. In our work with Bernard, we relied on this approach to help him discover concepts for himself. Initially, we introduced taking unit fractions of a unit fraction and taking non-unit fractions of unit fractions using fraction bars. However, representing more complex fraction relationships visually proved challenging with fraction bars alone. For problems involving fraction multiplication, we used the modeling method (see Figure 2).

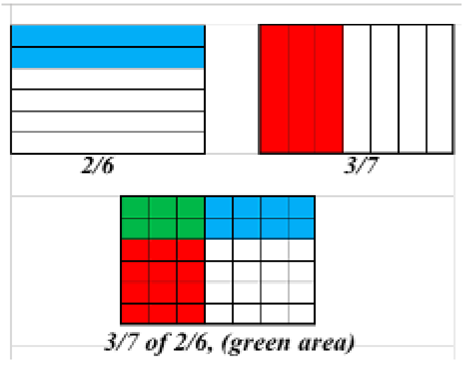


Figure 2. Modelling Method

In addition, we addressed fraction simplification so that Bernard could recognize when simplification was needed especially in problems involving larger numbers. We believe that procedural rules can be helpful for efficiency, but they should be introduced after students have developed the underlying concept for themselves. Our goal was not only for Bernard to be able to solve fraction problems correctly, but also to be able to model them independently and apply his understanding when faced with more complex tasks in the future. Even though sixth-grade students may not typically encounter highly complex fraction problems, a strong conceptual foundation at the primary and middle school levels has long-term benefits for future learning.

After instruction, we presented two interview problems to assess Bernard's progress with fraction multiplication one focusing on unit fractions of a unit fraction, and the other on general fractions of fractions.

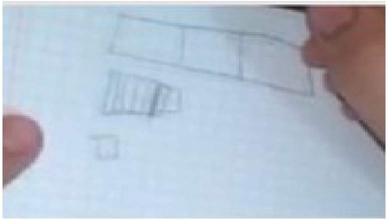


Figure 3. Bernard's Picture

Protocol 5

Question: Bekir reserved 1/3 of a cake for himself. Later, he divided that portion into 7 equal parts and took 1 part for himself. What is the ratio of the cake Bekir allocated for himself to the whole cake?

Student's Process:

Bernard drew a rectangular cake and divided it into three equal parts. He then divided one of those parts into seven equal sections.

Researcher: What fraction of the whole cake did Bekir keep for himself?

Bernard: 1/21.

Researcher: How did you get 21?

Bernard: Each piece has 7 parts. Three pieces together make 21 parts, so it's one part out of 21.

This problem involved taking a unit fraction of a unit fraction. While a student who is already comfortable with natural number multiplication could quickly be shown the rule for multiplying fractions, we chose instead to let Bernard discover the relationship himself. He used fraction bars (see Figure 3) to model the problem step-by-step, arriving at the correct answer without difficulty. This approach allowed him to generalize the idea for more complex situations. Students taught only procedural rules often struggle with problems presented in unfamiliar formats, whereas Bernard's conceptual understanding helped him solve the problem with confidence.

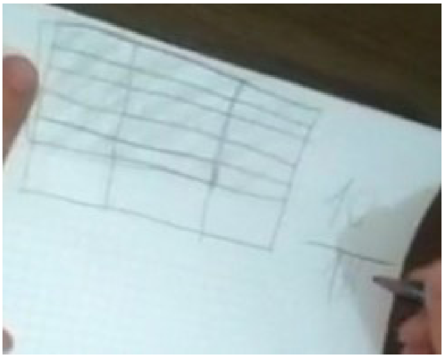


Figure 4. Bernard's Picture

Protocol 6

Q6. Enes answers (5/6) five-sixths of the questions in the exam. Since (2/3) two-thirds of the questions answered by Enes are correct, what is the ratio of the questions Enes answered correctly to all questions?

Bernard: The student read the question and started. First, he drew a rectangle and divided it horizontally into 6 parts. Then he divided it into 3 parts vertically by the Modeling method. T- What have you done so far?

Bernard: First I drew five-six, then two thirds. The areas that were painted together are important to us, we will count them. There are 10 we are writing here. All of them have 18 in total. So here we find that 2/3 of 5/6 is 10/18.

Researcher: Ok, thank you.

It was difficult for the student to reach a solution by using the fraction bars program in fractions with different numerators and denominators, and it was not successful in reaching a solution. Therefore, as we asked in Protocol 6, the student's use of the modeling method in questions helped him explore better. Bernard chose the table we used in the modeling method as in Figure 4 when solving the question and thus did not have difficulty solving the question.

This problem required multiplying fractions with unlike denominators. In this case, using fraction bars was less effective, so Bernard chose the modeling method. This visual strategy helped him work through the problem systematically. He demonstrated clear understanding of both the concept and the procedure, and his solution was correct and simplified.

Across the two protocols, Bernard consistently demonstrated progress in conceptualizing fraction multiplication. In Protocol 5, he was able to model a unit fraction of a unit fraction using fraction bars, reasoning his way to the correct answer without relying on memorized procedures. In Protocol 6, he successfully applied the modeling method to a problem involving unlike denominators, again reaching the correct and simplified solution.

These findings suggest that introducing multiplication of fractions through discovery-based methods—such as fraction bars and the modeling method—can help students build strong conceptual foundations before learning formal rules. Once these rules are introduced, students can connect them to the underlying meaning, making them more adaptable to non-routine problems. In Bernard's case, the gradual transition from visual models to symbolic rules seemed to support both understanding and fluency.

Older Students' Fractions Knowledge

In a first author's experience in teaching math for 11th graders in Ethiopia, she faced some students who had difficulty in computing fractional numbers. For example, she was teaching about the equation of ellipse, which is in the curriculum for 11th grade. After class, one of her students asked her about a line of calculation while the student said he understands how to find the equation of ellipse. She reminded that was "5-9/2=1/2" because it was surprising for her that an 11th-grade student could have difficulty in the computation of fractional numbers, not the equation of ellipse, which is their challenging task in their grade. These experiences led her to study more in the Mathematics Education field in order to find the reason and solution that can help those students. That example is one of her experiences. We had more students having difficulty in calculating fractional numbers, even though they learned fractional numbers in elementary school.

Through her experience, we came up with four ideas for reasons why older students have difficulty in fractional knowledge and how to figure them out. We investigated those reasons and solutions with reference books and articles of Steffe and his students. Four ideas are as below:

1. In view of *reorganization hypothesis*, students might reorganize their fraction scheme based on previous arithmetic knowledge.
2. Many students have difficulty in understanding improper fractions. *Units coordination* could be a key for learning improper fractions knowledge.
3. Teachers need to know their students' *multiplicative concepts*. And

then, they are able to provide learning by corresponding level for more understanding fractions knowledge.

4. Many students learn fractional computation *procedurally* rather than visually. Thus, students do not understand fractions as *concept images* which includes all the mental pictures and associated properties and processes (Tall & Vinner, 1981), so it is easy to forget how to apply for solving questions.

In this paper, we respond to four ideas to understand the reason why older student's difficulty in fractions knowledge have even if they learned in their elementary school. To do so, we will try to find evidence of students' understanding fractions knowledge and suggestions for improving their fractions knowledge based on four goals.

From the authors' internship at undergraduate course of N101, Teaching and Learning Elementary School Mathematics, we experienced how to approach the reasoning of operation in natural numbers and fractions with strategies. Most of the strategies were expressed as drawing and students were needed to draw by themselves every class. It was very new for us because basic operations such as addition, subtraction, multiplication, and division are too basic to draw for me, so we had limited experiences to draw them. However, we realized visualizing and explaining strategies by means of students' words are helpful for students to understand operations and even helpful to understand fractional knowledge deeply.

Students have an image of fractional numbers as part of a whole, so they have difficulty understanding improper fractional numbers because it needs to know improper fraction could be beyond a whole. In Hackenberg and Lee's (2015)2015 research, a student figured out improper fractions by using the concept of refill of cake. It infers, in specific context, students can figure out the meaning of improper fractions visually. This kind of example can be a clue to starting to understand improper fractions. We believe that visualizing fractional knowledge with specific object can be helpful to have fractions concept image for children before enabling abstract thinking of fractions. And units coordination can be helpful for students to interiorize their fractions knowledge by visualizing fractions as well as imagining fractions with mental actions. In this chapter, we demonstrated how to interiorize fractional knowledge and make a scheme by using units coordination.

Reorganization Hypothesis

The basic hypothesis in this paper is the *reorganization hypothesis*. Steffe and Olive (2010) coined that one could consider the new way of knowing to be a rearrangement of the prior way of knowing when it is built using the prior way of knowing in a creative way. The *interference hypothesis*, which is a widely held opinion that natural number knowing interferes with fractional knowing, stands in contrast to the reorganization hypothesis (Steffe & Olive, 2010). As a result, when children answer fractions problems, they are seen to operate on natural numbers in a manner that is inconsistent with their operations on fractions.

Children can construct their fractions scheme by eliminating *perturbation* by making *accommodation*. *Perturbation* is defined as either disappointment or surprise and it may lead to all sorts of random reactions (von Glasersfeld, 1995). Accommodation is an act of learning in two cases. Firstly, if the activity's unanticipated result disappointed you, one or more of the recently observed traits might alter the recognition pattern and, consequently, the circumstances that will set off the activity again in the future. Secondly, if the unexpected result was enjoyable or intriguing, a new scheme will be established, incorporating the new attribute into an existing recognition pattern. For example, when children have an animal knowledge with their dog, the first time they see a deer, they might regard it as a dog because they cannot find any difference between dog and deer. However, once their parents say it is a deer because it has antlers that a dog does not have, the children will extend the animal scheme to include deer. In other words, the children can figure out differences and similarities between dog and deer, so they can do accommodation of their animal scheme as forming a new scheme of deer. In the same way, once fractions are given to children, they would apply the way of natural numbers to the fractional problems. However, they would figure out they are not the same by having incorrect answer, so they might try to find the different ways to fit in fractions. This process is learning fractions by extending their number scheme from natural numbers to rational numbers including fractions. Moreover, children would make a new fraction scheme.

Based on the reorganization hypothesis, instead of concentrating on interference from prior natural number knowledge, we believe educators should support students in building their understanding of fractions through accommodations in their own natural number knowledge. According to Steffe and Olive (2010), partitioning or splitting operations and iterable units in fractions knowledge can be incorporated into the same psychological framework as doing so in natural number knowledge. In other words, splitting and sequencing come from operation experiences in natural numbers knowing.

Students' Units Coordination

Composite units play an important role in understanding students' fractional knowledge. Thus, a way of generating and coordinating composite units helps students understand multiplicative concepts. In Hackenberg and Lee's (2015)2015 research, there are three types of multiplicative concepts: the *first* multiplicative concept (i.e., stage 1), the *second* multiplicative concept (i.e., stage 2), and the *third* multiplicative concept (i.e., stage 3). According to estimates made by Steffe (2007), at least two levels of interiorization were completed by 50–70% of newly enrolled sixth graders. That means there are more than half of students who are at stage 2 or stage 3 while there are over 30% of students at stage 1. In other words, teachers can see students with various levels of multiplicative concept, so they need to be prepared for what to do for each of them. We would like to discuss how teachers can help each level of students to understand fractions of knowledge.

Table 3 shows the percentage of students in grades 5-8 at each units coordination stage. Since students learn fractions in grades 5 and 6, and fractional knowledge requires multiplicative reasoning, the number of students at stage 1 highlights a challenge in constructing fraction knowledge (Hackenberg & Sevinc, 2024).

Table 3. Units coordination stages for grades 5-8, including percentages (Acar & Sevinç, 2021)

Grade level	Stages of units coordination			Total
	Stage 1	**Stage 2**	**Stage 3**	
5	13 (52.0%)	9 (36.0%)	3 (12.0%)	25 (18.0%)
6	10 (47.6%)	10 (47.6%)	1 (4.8%)	21 (15.1%)
7	25 (48.1%)	22 (42.3%)	5 (9.6%)	52 (37.4%)
8	14 (34.1%)	25 (61.0%)	2 (4.9%)	41 (29.5%)
Total	62 (44.6%)	66 (47.5%)	11 (7.9%)	139 (100%)

Students operating at Stage 1

Students at stage 1 are able to coordinate two levels of units in an activity, but they are unable to accept a provided unit of units or composite unit (Hackenberg, 2013)2013. For example, stage 1 peers cannot imagine five parts in a unit ahead of operating. However, they can make five parts *in activity* by partitioning five parts from a whole unit. And they can find three-fifths by shading three parts among five parts. In this regard, students at stage 1 have a tendency to construct *parts-within-wholes fraction schemes* (PWWFS) (Steffe & Olive, 2010). It brings the problem that fractions cannot go beyond a whole, so students at stage 1 typically struggle with constructing improper fractions.

In Olive & Vomvoridi's (2006) research, Tim was a student at stage 1. When he was given to solve '1/2 + 1/4', he shaded one of two parts and all four parts and then added both regardless of the size of a part. So, he concluded '1/5' as an answer. At first, he hadn't built a disembedding operation. Nevertheless, by combining focused interview exchanges with updated classroom instruction, over the course of a month Tim constructed a *partitive unit fraction scheme* (PUFS). Students with PUFS go beyond solely part-whole ideas (Hackenberg, 2013)2013. It shows some students at stage 1 can construct robust fractional knowledge with targeted intervention. Actually, they do not typically make the kind of development that Tim has. Students at stage 1 in other studies have continued to use the first multiplicative concept for at least two years despite receiving ongoing instruction from researchers with training (Steffe & Cobb, 1988).

Students operating at Stage 2

For students at stage 2, it is possible to do units coordination as two composite units ahead of operating. For instance, students at stage 2 can imagine five parts of a unit partition, but they cannot partition a 5-unit bar into 7 parts in order to get a unit of 35 parts without activity. Thus, they can imagine a 5-unit bar without activity, and then they need to partition 7 parts in each of 5 parts. So, they can get 35 parts after the activity. Composing a unit and five parts in a unit means students have a second multiplicative concept (i.e., stage 2). And composing a unit, five parts in a unit, and seven parts in each five parts means students can think of three-levels-of-units concept which is not possible for students at stage 2. In other words, students at stage 2 can interiorize units of units by having a view of the result prior to the activity. Nevertheless, they are unable to project a three-level unit structure in the fraction bar.

In Hackenberg and Lee's (2015)2015 research, two students at stage 2 articulated verbally that drawing an improper fraction was strange. For example, Lisa said, "That's weird . . . can there be nine sevenths?" (p. 211) and added, "you can't take nine out of something that's seven" (p.211). She also drew nine parts less than a unit bar by partitioning seven parts with the small two last parts and dividing the first two parts equally in order to make nine parts in a bar. Thus, the researchers did not attribute an iterative fraction scheme to Lisa. How is this related to what you have said above about students at stage 2?

Students operating at Stage 3

For students at stage 3, it is possible to make a three-levels-of-units structure. Thus, students at stage 3 can conceive of 35 as seven 5s and as five 7s. That means students at stage 3 can imagine partitioning a 5-unit bar into 7 parts in order to get a unit of 35 parts without activity because they interiorized three-levels-of-units structure. It is powerful to construct any fractions and operate them.

In Hackenberg and Lee's (2015)2015 research, Suzanne's drawing was representative of the responses of students at stage 3. In her drawing, she explained her reasoning as follows: "I divided this [original bar] up into sevenths, and then I drew out the whole bar, and then, I here [pointing to the right and of the copy of the whole bar] I kind of measured how much two sevenths would be, and added it to the end of the bar" (p.214). She also explained the size of one of the parts, Suzanne called it "one seventh of this bar [pointing to the original bar] or one ninth of this bar [pointing to the new bar]." She had therefore created a reversible iterative fraction method, according to the researchers. How does this relate to what you have said about students at stage 3?

Partitive and Iterative Fraction Schemes

Operations: Partitioning, Disembedding, and Iterating

Operations are mental actions, like conceiving of subdividing a unit into equal parts (Piaget, 1970; von Glasersfeld, 1995). For fractional knowledge, some key operations are *partitioning* of a unit, *disembedding* one of partitioning parts, and *iterating* as many as we need. For example, when students are given to draw seven-fifths, firstly they can draw a unit bar, and then they can partition it into five equal parts. Secondly, they need to disembed one-fifth part of a unit-bar. Finally, they iterate seven times of one-fifth in order to get seven-fifths. This process shows the operations of partitioning, disembedding, and iterating.

The Partitive Fraction Scheme

Steffe (2001) determined that the first system that qualifies as a true fractional scheme is a *partitive fractional scheme*. A student who learns fraction as a part out of whole considers one-third of a candy bar as a part of that. When 1/3 iterates three times, it will produce a three-parts bar. To make two-thirds of a candy bar, a student will divide into 3 parts of a candy bar first, pick one-third secondly, and then iterate it two times in order to make it as two-thirds. This implies that a unit fractional part of the partitioned whole can be disembed and then iterated to create another unit fractional part of the partitioned whole. However, enabling to disembed and iterate a unit fractional part does not mean those students are able to understand improper fractions such as four-thirds. In other words, these students cannot think out of the whole so they cannot conceive fractions that are greater than the unit.

The Iterative Fraction Schemes

A significant challenge in students' fractional knowledge is an *iterative fractional scheme* (Olive & Steffe, 2002; Tzur, 1999)Steffe (2002. It starts from unit fractions as iterable units. If students have an iterative fractional scheme, they are able to find unit fractions and then make a whole by iterating the unit. For example, in order to find five-thirds, students who have an iterative fractional scheme can find one-third as a unit fraction, and then they do five times of one-third to get five-thirds. Moreover, they are enabled to consist whole by iterating three times of one-third (Hackenberg, 2007)2007.

Research Examples

In Hackenberg's (2007)2007 research, Deborah did not show the construction of improper fractions initially. When she was given to draw seven-fifths by hand, she expressed some dismay. To be specific, Deborah stated that she drew the entire bar and didn't shut it until she had figured out how long two-fifths of the original bar were since she knew that seven-fifths equaled "one and two-fifths." Thus, Hackenberg (2007)2007 concluded Deborah gave examples of typical notions from pupils using partitive fractional schemes, and she deduced that seven-fifths did not yet mean one-fifth repeated seven times for them.

After 12 days, Deborah had another teaching episode about making a bar that was two-fifteenths longer than a 13/13-bar. In this episode, Hackenberg used JavaBars which is useful to show splitting and iterating with correct size in a fraction bar. Deborah drew a unit bar with 15 pieces, took away a 1/15-part from the 15/15-bar and extended the bar by two-fifteenths of its original length. The researcher concluded that a bar two-fifteenths longer than a unit bar was both a whole unit bar and two-fifteenths more and seventeen-fifteenths of the unit bar for Deborah since she justified her claim that seventeen-fifteenths is greater than one. Deborah's approach involved building a unit fraction as a unit that could be separated from and repeated beyond of the whole, creating a new unit of unit fractions that was still related to the entire but did not rely on part-whole connections. Thus, Hackenberg attributed an iterative fractional scheme to Deborah.

We think it is a strong strategy to partition a fraction bar and iterate a unit fraction by the given numerator, because student can recognize a unit fraction as the smallest part of a whole and make any number of fractions by iterating. Initially, when Deborah had improper fraction seven-fifth, she divided it by one and two-fifth before drawing. Therefore, she drew one bar and hesitated to close the fraction bar because she would like to make sure how much is two-fifth more. However, after having a notion of partitioning and iterating, she might partition as five pieces first, and then she will pull out one-fifth and iterate it seven times in order to make seven-fifth. This way is clear to express the corresponding size of seven-fifth.

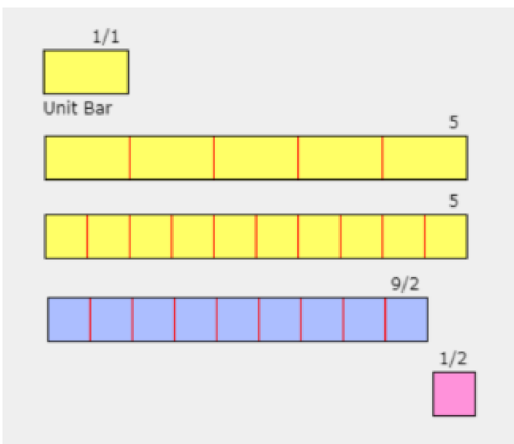
Procedural Barriers in Fractions Learning: Toward Conceptual Understanding

We have seen many teachers use procedure-based teaching style because they do not have enough time to do activities based on the allotted curriculum corresponding grades. In other words, teachers feel they have to address particular topics on particular days because there is pressure to "cover" topics. However, when students memorize the procedures as rules rather than understand by using visual methods and notations, they easily forget procedures in fraction operations such as addition, subtraction, multiplication, and division. We think if students need to remind how to operate fractions, using visualization examples with notation could be helpful for students to understand fractions knowledge better as well as remember it

From Rules to Reasoning: Using Drawing and Notation as Conceptual Tools

In our N101 internship class, we were not accustomed to draw and explain fractional computations, so we were not able to understand the drawings immediately. Soon after writing notation by instructor Dr. Hackenberg, however, it was clear to understand procedure of units coordination, so we felt our fractional knowledge became more powerful and flexible to think of. The notation was word expression of the drawings regarding units coordination. For example, notation '7/5 = 7 X 1/5' shows seven-fifth is equal to seven times one-fifth. It infers to partition a bar by five, disembed one-fifth as unit of unit, and iterate seven times in order to get seven-fifth. We think most of students who have learned fractional knowledge procedurally could be the same as me. If students can have the opportunity to learn fractions knowledge with drawing and notation, they would have more powerful fractions knowledge.

When the first author's 11^{th} grade student in Ethiopia asked the reason why '5-9/2=1/2', she just explained the rules of fractions operation procedurally. In this moment, she shared that she regrets her reaction for the question because it was about not reasoning mathematically but memorizing procedurally. If she would give to his visualization and notation together like in Figure 5, he might form more robust fractions scheme as well as remind fractions operation. When students start to drawings of quantities and build the notation from that, both young and older children, it can be helpful to understand fractions knowledge as well as make robust fractions knowledge.



Notation:

$$5 - \frac{9}{2} = ?$$

$$5 = \frac{10}{2}$$

$$\frac{10}{2} - \frac{9}{2} = \frac{1}{2}$$

Figure 5. Visual Fraction Bar with Drawing and Notation

Fractions as Quantities, Not Symbols

Fractions can be thought of as measurable extensive quantities when students are required to illustrate fractional amounts in units of measurement using rectangles or segments (Hackenberg, 2010)2010. For example, if students can consider fractions as quantities, they can imagine the length of 9/2cm and 5cm and compare them in order to subtract 9/2cm from 5cm.

Furthermore, it is a noteworthy achievement when children see fractions as lengths instead of as parts of wholes (Steffe & Olive, 2010).

Conclusion

In the first section, we emphasized fractions as a foundational concept in STEM education. Because all STEM areas involve numbers including fractions understanding fractions conceptually is essential for students. If students develop only a procedural understanding, this can hinder their ability to make sense of more advanced mathematics and STEM concepts. Conceptual understanding of fractions involves the ability to coordinate multiple levels of units and maintain this structure while working with them. We introduced this idea through the concept of units coordination.

Radical constructivism can serve as a lens for examining students' thinking in mathematics and across the broader STEM disciplines. This perspective holds that every student brings valuable experiences and can build new concepts upon their prior knowledge. For teachers, this underscores the importance of understanding students' thinking as a central part of instruction. We also discussed how this perspective can be implemented in classroom contexts by comparing it with the Emergent Perspective. Specifically, we presented our interpretation of Cobb and Yackel's work, first describing how the Emergent Perspective evolved from von Glasersfeld's Radical Constructivism, then explaining the limitations Cobb and Yackel identified in applying the theory to Developmental Research. We also noted how they incorporated aspects of Interactional Theory to address these limitations.

We examined the Emergent Perspective as an interpretive framework for Developmental Research. The constructs of Classroom Social Norms, Socio-mathematical Norms, and Classroom Mathematical Practices are key elements of the classroom micro-culture that Cobb and Yackel found important to account for. Each construct reflects individual aspects beliefs about one's own role, others' roles, and the nature of mathematical activity; mathematical beliefs and values; and mathematical conceptions and activity. These individual and social aspects cannot be fully understood in isolation they must be considered together.

As a final note on theory, we highlighted Cobb and Yackel's (1996) claim that the Emergent Perspective "locates students' mathematical development in social context while simultaneously treating learning as an active [individual] constructive process" (p. 173). The choice between a psychological perspective, a socio-cultural perspective, or an emergent perspective depends on the specific research questions and goals. Sociocultural perspectives may be especially valuable for examining cultural diversity and reform, while a purely psychological perspective can be useful for deeply understanding individual learning processes.

From our case study on developing children's fraction knowledge, we found that understanding a student's true grasp of fractions means going beyond memorized rules to see how they approach and solve problems. Memorized rules can be forgotten, and their use does not necessarily indicate genuine learning. While state education policies, curricula, and textbooks may claim to support student-centered learning, in practice, instruction often defaults to rule-based teaching because it is faster and easier. In student-centered approaches, students should be guided to discover concepts themselves, rather than simply being told definitions and procedures. However, textbooks that give answers immediately after each question, or curricula that label themselves "constructivist" without truly supporting discovery, can hinder this process.

In our study, the student showed gaps in fraction concepts that should have been learned in primary school likely forgotten or never understood conceptually. We used Fraction Bars and the modeling method to help the student discover the meaning of multiplying fractions. While our one-month study cannot definitively prove lasting learning, the final interviews showed improvement in the student's problem-solving. We therefore recommend approaches that move away from rule-based teaching toward discovery-oriented methods. We also found that Fraction Bars are useful for supporting conceptual understanding, and that the modeling method is particularly effective for more complex fraction problems.

From the section on older students' fraction knowledge, we suggest four instructional goals for teachers: (1) Extend number domains: Guide students from natural numbers to integers and fractions, helping them connect and contrast these number types, (2) Develop fractional schemes: Use Steffe's operations (partitioning, disembedding, iterating) with units coordination to deepen understanding, including improper fractions, (3) Advance multiplicative concepts: Support students in moving from stage 2 to stage 3, emphasizing iterative fraction schemes, and (4) Use visualization and notation: Incorporate drawings and concise notation to strengthen conceptual understanding for students who have learned fractions procedurally.

Although this chapter focused on a specific mathematical concept, fractions, its implications extend to all STEM fields. Many STEM concepts, whether in physics, engineering, chemistry, or computer science, require interpreting and manipulating proportional relationships, ratios, and part whole reasoning skills rooted in fraction understanding. Strengthening these skills in mathematics can therefore directly benefit learning and problem-solving across STEM disciplines. Moreover, radical constructivism's emphasis on connecting new ideas to prior knowledge can guide teaching practices in any STEM subject, encouraging students to actively build understanding rather than passively receive information.

Additionally, we suggest four future research directions: (1) Longitudinal studies to track how conceptual fraction understanding in early grades impacts later STEM learning and career readiness, (2) Classroom-based experiments testing how tools like Fraction Bars and modeling methods affect learning outcomes in diverse student populations, (3) Cross-disciplinary studies exploring how fraction-related reasoning supports problem-solving in other STEM subjects, such as interpreting scientific data or scaling engineering designs, and (4) Investigations into teacher preparation programs to examine how constructivist principles are taught, modeled, and applied in practice. By continuing to explore these connections and strategies, educators and researchers can better prepare students not only to master fractions but also to engage deeply with the full range of mathematical and STEM challenges they will encounter throughout their education and beyond.

Ultimately, our work with Bernard reminds us that the heart of mathematics teaching lies in helping students make sense of what they do, not just in getting the right answer. When students are given the space to explore, represent, and connect ideas, they begin to see mathematics as something they can understand and even enjoy rather than as a set of rules to memorize. This shift in perspective can spark curiosity, build confidence, and lay a stronger foundation not only for future mathematics learning but for success across all STEM disciplines.

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Chapter 4

STEM and Technology: Transforming Education

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Chapter Highlights

This chapter provides a concise overview of STEM learning as a modern, technology-integrated educational approach that supports student engagement, meaningful learning, and the development of 21st-century competencies.

- Examines the concept, characteristics, and scope of STEM learning as a contemporary approach adaptable to school-based, home-based, and virtual learning environments.
- Explores the integration of emerging technologies, such as robotics, artificial intelligence, simulations, and virtual platforms, in supporting interactive and project-based STEM learning.
- Highlights the role of STEM instruction in improving student engagement, enjoyment, and learning outcomes through hands-on and technology-supported activities.
- Discusses how STEM learning strengthens essential 21st-century skills, including critical thinking, creativity, collaboration, communication, and problem-solving.
- Presents practical examples and case studies of STEM implementation at different educational levels to support effective classroom practice.
- Addresses key challenges in implementing STEM education, such as infrastructure limitations, teacher readiness, and unequal access to technology, while identifying emerging opportunities for STEM development.

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INTRODUCTION

Basic Concepts of STEM in Education

STEM (Science, Technology, Engineering, and Mathematics) education is a learning approach that integrates four main disciplines in an interdisciplinary manner (Maass et al., 2019; Mcdonald, 2016). STEM not only teaches theoretical concepts but also encourages students to develop critical thinking, problem solving and innovation skills through practice-based projects (Mu'minah, 2021). The STEM approach to education aims to equip students with the 21st century skills needed in the world of work, such as creativity, communication and collaboration (Honey et al., 2014). The basic concepts of STEM emphasize project-based learning and interdisciplinary approaches that enable students to apply scientific concepts in real-world situations (Margot & Kettler, 2019). Thus, STEM education does not only focus on theory but also on practical applications that are relevant to everyday life. This aims to build a more interesting and meaningful learning experience for students.

STEM education also emphasizes the integration of disciplines into a single, complex project or problem. For example, in a mini-bridge building project, students not only learn about the laws of physics and mathematics involved in bridge design, but also use technology to model and engineer the structure of the bridge (Honey et al., 2014). Thus, STEM provides opportunities for students to develop more holistic, cross-disciplinary skills.

One important aspect of STEM education is the role of technology in supporting the learning process. Technology is used to enhance students' understanding of STEM concepts through digital simulations, virtual laboratories, and interactive learning (Abdi et al., 2021; Sari* et al., 2022), as well as artificial intelligence (AI) based software that assists in data analysis and decision making (Xu & Ouyang, 2022). In addition, the use of robotics in STEM education is also a growing trend, students who are involved in robotic activities tend to be more motivated and challenged to explore more deeply. In addition, robotics training has also been shown to be effective in developing various other important skills, such as problem solving, teamwork, and creativity (Ramadhani & Zahrani, 2024).

STEM is an acronym for science, technology, engineering, and mathematics. The term was first launched by the National Science Foundation (NSF) of the United States (US) in 1990 as a theme for the education reform movement to grow the STEM workforce, develop STEM literate citizens, and increase the United States' global competitiveness in science and technology innovation

(Mccomas, 2014). In recent years, research in the field of STEM has proven that STEM can be applied in various forms such as project-based learning, laboratory experiments, and the use of digital technology in the learning process. The main advantage of STEM education lies in its ability to integrate theoretical concepts with practical applications, thus equipping students with the skills needed to face challenges in the industrial world and future technological developments.

The implementation of STEM education in the school curriculum faces various challenges, many factors cause the lack of implementation of STEM project learning in schools. The lack of teacher control over the pace of the curriculum and its consequences for teaching is also considered a challenge for teachers in their efforts to integrate interdisciplinary subjects for authentic STEM lessons (Herro & Quigley, 2017), other barriers include administrative and financial support (Asghar et al., 2012; Ming-Chien Hsu et al., 2011; H. J. Park et al., 2016; M. H. Park et al., 2017), or lack of technological resources for students such as computers (Wang et al., 2011). Student concerns are another barrier to integrating STEM education. Sometimes, teachers feel that students are not capable enough or are not interested enough to be actively involved in STEM integration. Teachers also sometimes underestimate students' ability to solve STEM-related problems (Al Salami et al., 2017; Tuong et al., 2023; van Haneghan et al., 2015). Many teachers find some of the subject matter too difficult for students, which can lead to a decrease in student motivation. Teachers in rural areas are concerned because many of their students have low achievement, and adapting the curriculum to meet the needs of these students is a challenge (Goodpaster et al., 2018). These concerns may influence teachers' intentions, approaches, and success in implementing STEM teaching (Le et al., 2021). The limited number of teaching staff who have expertise in STEM and the difficulty in integrating four disciplines effectively in one learning requires training and professional development for teachers to improve their capacity in implementing STEM learning in the classroom. In addition, the involvement of industry and higher education institutions is also very important in supporting the development of better STEM education.

In some countries STEM education has become an integral part of national education systems. For example, in the United States, education reforms emphasize the need to develop the complex technology and engineering skills that students need to participate in a knowledge-based economy (Börner et al., 2018; van Laar et al., 2017; Wang et al., 2011)but their offerings sometimes misalign with commercial needs and new techniques forged at the frontiers of research. Here, we analyze and visualize the dynamic skill (mis-. Meanwhile, countries such as Finland and Singapore have systematically implemented the STEM approach in their curricula, with a focus on inquiry-based learning and problem solving (Murphy et al., 2023; Roy, 2019).

In general, STEM education plays an important role in preparing the younger generation to face global challenges in the Industrial Revolution 4.0 era. With the right approach, this education can support students in honing critical thinking, creativity, communication, and collaboration skills that are essential in the future world of work. Therefore, STEM education policies and implementation strategies need to be continuously developed in order to provide optimal benefits for students and the wider community.

The role of technology in STEM education

Technology plays a crucial role in STEM (Science, Technology, Engineering, and Mathematics) learning, acting as a catalyst that enriches the learning experience, increases student engagement, and prepares students for the challenges of the modern world. The integration of technology in education not only facilitates the understanding of complex concepts but also develops essential 21st-century skills, such as critical, creative, and collaborative thinking.

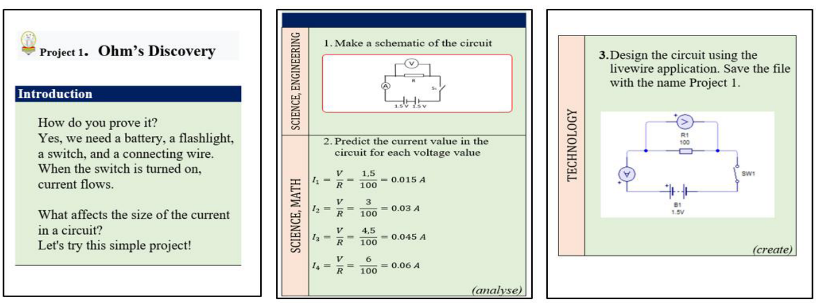

Figure 1. Example of Virtual Experiment and Placement of HOTS Elements (Yennita et al., 2022)Design, Develop, Implementation and Evaluation

The use of technology in STEM learning creates an interactive and dynamic learning environment. For example, augmented reality (AR) applications allow the visualization of abstract concepts to be more concrete, so that students can understand the material more deeply. A picture shows that AR applications in education can improve students' understanding of STEM material by making learning more interesting and interactive (Godoy Jr, 2022). In addition, with the existence of learning technology, STEM projects can be implemented well. The following is an example of a STEM project that is carried out virtually.

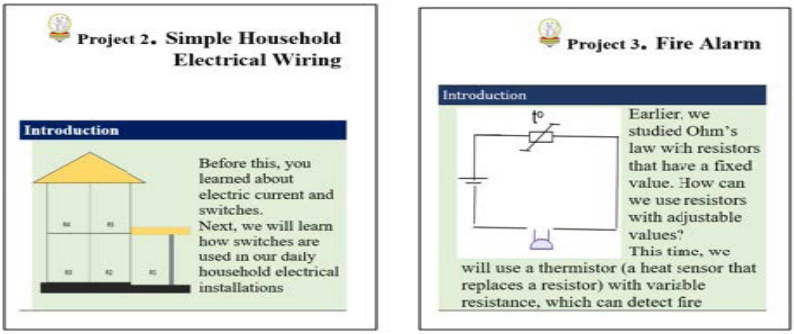

Figure 2. Example of a Virtual STEM Project (Yennita et al., 2022)Design, Develop, Implementation and Evaluation

The use of technology in STEM in addition to being used in virtual experiments, technology can also be used in building STEM projects virtually. The following are STEM projects that are built virtually.

By effectively leveraging technology, educators can create more meaningful and relevant learning experiences, preparing students for future challenges and opportunities. Thus, technology integration in STEM learning is not just an option but a necessity to ensure that education remains relevant and adaptive to the times.

The Importance of Technology Integration in STEM

The integration of technology in STEM (Science, Technology, Engineering, and Mathematics) education plays a crucial role in preparing the younger generation to face the challenges of the digital era. The application of technology in STEM learning not only improves students' conceptual understanding but also develops 21st-century skills such as critical thinking, creativity, collaboration, and digital literacy.

One of the main benefits of integrating technology into STEM education is the enhancement of critical thinking and problem-solving skills. Through the use of digital tools and platforms, students are encouraged to analyze data, identify patterns, and solve complex problems with a systematic approach. For example, the use of virtual laboratories allows students to conduct scientific experiments without the constraints of space and time, so that students can test hypotheses and see the results directly. This is in line with research showing that the use of technology in STEM learning can improve students' analytical and problem-solving skills (Hafizah Hussin et al., 2019)Technology, Engineering and Mathematics (STEM.

In addition, technology integration encourages creativity and innovation in learning. The use of devices such as microcontrollers and sensors in science projects allows students to design and build prototypes that solve real-world problems. This approach not only makes learning more interesting but also facilitates students to apply theoretical concepts to real-world practice. For example, a technical toy-making project has been implemented in Vietnam to integrate STEM education, where students are directly involved in the design and construction process, thereby enhancing their technical understanding and skills (Quang et al., 2015).

Collaboration is also an important aspect that is strengthened through the integration of technology in STEM education. Digital platforms and communication tools allow students to work together on group projects, even if they are in different locations. This teaches students teamwork skills, effective communication, and project management. Additionally, collaboration with the tech industry can provide students with practical insights and real-world experiences, preparing them for the real world of work. Collaborations between schools and tech companies, such as the provision of IoT devices and hands-on training from industry professionals, have been shown to improve the quality of learning and the relevance of the curriculum to industry needs.

Digital literacy is also an essential component gained through the integration of technology in STEM education. Students not only learn to use devices and applications, but also understand the working principles behind the technology. This understanding is important so that students can adapt quickly to technological developments and become innovators in the future. For example, the introduction of robotics in the STEM curriculum helps students understand the concepts of programming and mechanics, which are the foundation of many modern technologies.

The implementation of technology integration in STEM education is not without challenges. Limited resources, such as lack of technological devices and internet access, as well as the need for adequate teacher training, are obstacles that need to be overcome. Therefore, support is needed from various parties including the government, educational institutions, and the private sector, to provide the necessary facilities and conduct training programs for educators. In addition, the development of a flexible and adaptive curriculum to technological developments is also the key to success in this integration (Davidi et al., 2021). Overall, the integration of technology in STEM education is a strategic step to prepare a competent and adaptive young generation in the digital era. By utilizing technology as a learning tool, students not only gain theoretical knowledge, but also practical skills that are relevant to the needs of the times. This is in line with the goal of education to produce individuals who are able to contribute positively to society and are ready to face the dynamics of technological developments in the future.

Technological Developments in the World of Education

Technology has experienced rapid development in the world of education, giving a significant impact on learning methods and interactions between educators and students. Along with the emergence of the industrial revolution 4.0, various technological innovations have begun to be applied in education, such as the use of artificial intelligence (AI), big data, the Internet of Things (IoT), and augmented reality (AR) and virtual reality (VR). These technologies not only help in increasing the effectiveness of learning but also enrich students' learning experiences with a more interactive and innovative approach (Pratama & Setiawan, 2022).

In the digital era, information and communication technology (ICT) has become an integral part of the world of education. Since the introduction of computers in the education system in the late 20th century, technological developments have continued with the emergence of the internet which has changed the way information is accessed. The internet today allows students to obtain wider learning resources ranging from electronic books, scientific journals, online courses, and students can conduct virtual experiments. In addition, Learning Management Systems (LMS) such as Moodle, Google Classroom, and Edmodo are also important tools in online learning that allow for more flexible interaction between teachers and students (Einggi Gusti Pratama & Andhyka Kusuma, 2021).

Other technologies that have had a major impact on education are virtual reality (VR) and augmented reality (AR). Using VR and AR, students can experience deeper and more immersive learning, especially in the fields of science, technology, engineering, and mathematics (STEM). For example, in biology learning, VR allows students to explore human anatomy interactively without having to use real specimens (Khuzeir Tarmizi et al., 2021).

Although technological developments in education bring many benefits, challenges still remain. One of the main challenges is the gap in access to technology, especially in remote areas or developing countries that still have limited internet infrastructure and digital devices. In addition, teacher readiness in adopting technology is also a determining factor in the success of implementing technology in education. Therefore, training and improving digital literacy for educators is essential to ensure optimal use of technology in learning.

Overall, technological developments in education have brought about a major transformation in the way teaching and learning take place. From the use of the internet to artificial intelligence and virtual reality, technology continues to evolve and provide various solutions to improve the quality of education. However, the success of implementing technology in education still depends on the readiness of infrastructure, teacher training, and education policies that support digital innovation in learning.

Challenges and Opportunities in STEM Implementation

The implementation of STEM (Science, Technology, Engineering, and Mathematics) education in Indonesia faces various challenges that require serious attention. One of the main challenges is the limited facilities and infrastructure in many schools, especially in remote areas. Many schools in Indonesia do not have adequate science laboratories, technological equipment, or stable internet access. These limitations hinder effective learning processes and limit students' opportunities to engage in practical activities that are essential in STEM education. In addition, the readiness and competence of teachers in teaching with a STEM approach is also a significant challenge. Many educators have not received adequate training to integrate science, technology, engineering, and mathematics in learning. This has an impact on the lack of confidence and effectiveness in delivering STEM material holistically and interdisciplinary.

Lack of resources and appropriate learning materials is also a barrier. Schools often lack relevant and up-to-date teaching materials and teaching aids that can support STEM learning optimally. These limitations make the learning process less interesting and less able to facilitate the understanding of complex concepts in STEM. On the other hand, the implementation of STEM education in Indonesia also opens up various opportunities that can be utilized to improve the quality of education. One of them is the increasing government support for the development of STEM-based education. This initiative includes the integration of the STEM curriculum into the national education system and the provision of training programs for teachers to improve student competency in teaching with a STEM approach. Overall, although there are various challenges in the implementation of STEM education in Indonesia, the opportunities that exist provide hope for further improvement and development. With a joint commitment between the government, educational institutions, industry, and society, STEM education can be an important pillar in preparing a competent young generation of Indonesia who are ready to compete in the era of globalization.

Artificial Intelligence (AI) and Machine Learning in STEM Education

The development of Artificial Intelligence (AI) technology has had a significant impact on the world of education, especially in the fields of Science, Technology, Engineering, and Mathematics (STEM). AI helps improve the learning experience by providing an adaptive learning system that can adjust materials according to student needs. AI in education can optimize data-based learning to provide more personalized recommendations for students. On the other hand, AI contributes to project-based learning and experiments in STEM, where AI-based systems can help students design, test, and analyze experiments more efficiently. However, the main challenge in implementing AI in STEM education is the readiness of the infrastructure and skills of educators in utilizing this technology. The application of AI in education requires intensive training for teachers so that students can effectively integrate this technology into learning. In addition, there are also ethical challenges related to the use of student data that require strict regulations to protect the privacy and security of student information (Selwyn, 2019). With the continued advancement of AI and ML, STEM education can become more inclusive, efficient, and responsive to student needs. Therefore, the integration of this technology must continue to be encouraged with supportive policies and the development of teacher and student competencies in operating AI-based systems in the classroom.

Robotics as a STEM Learning Medium

Robotics plays a vital role in STEM (Science, Technology, Engineering, and Mathematics) education by providing interactive, innovative, and hands-on learning experiences. The use of robotics in learning enables students to understand abstract concepts in STEM through hands-on experiments, which ultimately enhances students' understanding of science and technology (Jung & Won, 2018). Thus, the integration of robotics in education not only helps students in developing technical skills, but also critical thinking, problem solving, and collaboration skills.

In science, robotics helps students understand the principles of physics, biology, and chemistry through robot-based experiments. For example, sensors on a robot can be used to measure temperature, light, or gas levels in an environment, allowing students to conduct hands-on scientific experiments (Sapounidis & Alimisis, 2020). In the field of technology and engineering, robotics allows students to design, build, and program robots that strengthen students' understanding of mechanical systems and programming (Eguchi, 2016). With these skills, students not only learn technical concepts but also understand how to apply them in real life.

In addition, robotics also enhances computational thinking and programming skills which are an integral part of the STEM curriculum. Robotics-based learning allows students to understand programming concepts practically through simple coding and algorithms implemented in robots (Jung & Won, 2018). By learning programming through robotics, students not only gain technical skills, but also improve their ability to think logically and systematically.

Robotics also plays an important role in increasing student engagement in STEM learning. Several studies have shown that the use of robotics in education can increase student motivation to learn and make students more active in understanding STEM concepts (Nugraha et al., 2020). The project-based learning approach applied in robotics allows students to work in teams, develop innovative solutions, and solve real-world problems. Thus, robotics contributes to fostering collaboration and communication skills that are essential in the future workforce. However, the implementation of robotics in STEM education also faces several challenges, such as limited resources, high costs, and the need for adequate teacher training. Therefore, support is needed from various parties, including the government, educational institutions, and the technology industry to ensure that robotics can be effectively integrated into the STEM curriculum (Benitti, 2018). With adequate investment in robotics technology, it is hoped that students can gain maximum benefits from this innovative learning approach. Overall, robotics has a significant role in STEM education by providing a more engaging and meaningful learning experience for students. With the right application, robotics can help develop 21st-century skills needed to face future challenges, while increasing students' competitiveness in the digital era.

Using Video Tracker for Motion Analysis

The use of Tracker software in motion analysis has become an important innovation in physics learning. Tracker is an open source software specifically designed to analyze videos and model the motion of objects. By utilizing recorded videos, users can track the position, velocity, and acceleration of an object accurately, making it easier to understand the concepts of kinematics and dynamics in physics. In the context of education, Tracker has been used as a tool to improve students' understanding of the concept of motion. For example, research by Fitriyanto & Sucahyo (2016) shows that the application of Tracker software in kinematics motion practicum can improve students' science process skills. Students become more active in observing, measuring, designing experiments, interpreting data, and communicating. This is in line with the findings of Habibbulloh & Madlazim, (2014) who stated that the use of video analysis methods with Tracker software can improve students' science process skills in the concept of free fall motion. Research that has been conducted, learning using trackers can help students understand the concept of physics learning. The following is a picture of the results of learning analysis using video trackers.

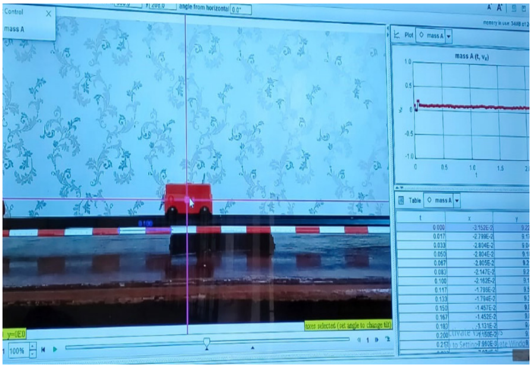

Figure 3. Uniform Linear Motion Experiment

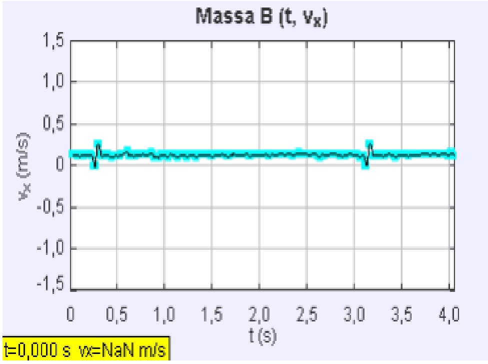

Figure 4. Graph of Uniform Linear Motion Experiment Results

Video Tracker is a digital-based software used to analyze motion in videos. This tool is widely used in physics learning to help students understand the concepts of kinematics and dynamics more concretely. With Video Tracker, students can record or take videos of an object's movement, then analyze its position, velocity, and acceleration frame by frame. The use of Video Tracker allows students to connect theory with real phenomena, thereby improving conceptual understanding and higher-order thinking skills. In addition, this application also trains multi-presentation skills, such as presenting data in the form of graphs, tables, and visual simulations. In technology-based learning, Video Tracker is an innovative tool that encourages scientific exploration and investigation. Through real-data-based analysis, students can develop analytical and problem-solving skills, which are important in STEM-based science learning.

Robotics Projects in STEM Learning

Implementation of robotic projects in STEM learning has been proven effective in improving students' understanding of science, technology, engineering, and mathematics concepts. Case studies in various educational institutions show that the integration of robotics in the curriculum not only enriches the learning experience but also develops 21st-century skills such as problem solving, critical thinking, creativity, and collaboration. One example of the application of robotics in STEM learning is at Joy Kids National Plus Tasikmalaya Kindergarten. There, STEAM extracurricular activities involving robotic coding games have been implemented to train problem-solving skills in early childhood. This approach involves children in unplugged coding activities that help students understand commands in a series, including direction and sequence. The results showed that children were able to develop observation, information gathering, analysis, and communication skills through this activity (Sopiah et al., 2023).

At the junior high school level, the introduction of robotics has also had a positive impact. Lego robot training for students at Bani Hasyim Junior High School (SMP) in Malang Regency, for example, has increased students' interest and understanding of technology and robotics. This activity involves exposure to materials and hands-on practice, where students assemble and program Lego robots to complete certain missions. After the training, 80% of participants expressed interest in studying robotics further, demonstrating the effectiveness of this approach in motivating students (Gumilang et al., 2023). Many studies have been conducted in the application of technology in STEM, research conducted by Yennita et al., (2020) developed a prototype electrical installation as a STEM project for junior high school students and in this study the research team succeeded in developing it. Furthermore, research conducted by Yoeliana et al., (2022) stated that the application of STEM project-based learning can improve students' creative abilities.

In addition, STEM-based robotics training has been conducted in one of the high schools in Bandung City. This training aims to teach physics concepts through robotics, which can foster STEM education and improve logical, creative, innovative thinking skills, and teamwork skills. The results showed that 90% of students understood the introduction to Arduino, analog signals, and programming languages; 98% of students were able to assemble robots; and 95% of students were able to connect programming languages to robots via Bluetooth. In addition, 85% of students understood how to analyze data through graphs and verify them with data from robots (Asri, 2018).

At the junior high school level, the implementation of STEM learning through Lego robot training has also been carried out. This activity involves the presentation of materials and direct practice, where students assemble and program Lego robots to complete certain missions. The results showed an increase in students' understanding of technology and robotics, as well as a high interest in studying the field further (Gumilang et al., 2023).

At the vocational high school level, robotics training and workshops have been provided to teachers and students of SMK Kesehatan Binatama Yogyakarta. This activity aims to improve understanding and skills in the field of robotics, especially in applications in the medical field. The results showed that the training participants gained basic knowledge of robotics and were able to design and program simple robots (Nur'aidha & Sugianto, 2022).

Overall, the above case studies show that the integration of robotic projects in STEM learning has a significant positive impact on the development of students' skills and understanding. This approach not only makes learning more interesting and interactive, but also prepares students to face the challenges of the modern technological era.

Project Based Learning Concept in STEM

Project-based learning in STEM (Science, Technology, Engineering, and Mathematics) education is an innovative approach that puts students at the center of learning. This method encourages students to learn through active exploration, solving real-world problems, and applying concepts across disciplines. In STEM, PBL allows students to develop critical thinking, creativity, communication, and collaboration skills that are essential to facing real-world challenges.

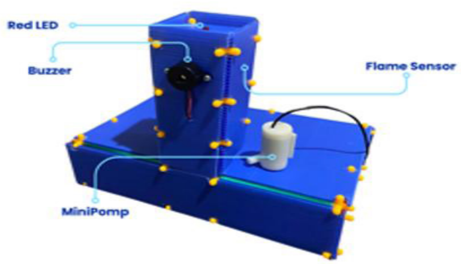

Figure 5. Fire Alarm

One of the key strengths of PjBL in STEM is its ability to connect theory to practice. Students not only learn abstract science and math concepts but also use them to design real-world solutions to complex problems. For example, a disaster mitigation project might incorporate physics principles into programming early warning systems such as fire alarms and flood alarms. This approach makes learning more meaningful and relevant to students. Here are some examples of STEM projects that leverage technology in the context of disaster mitigation.

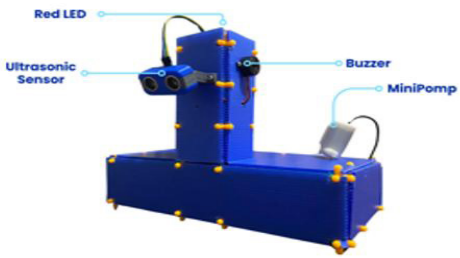

Figure 6. Flood Alarm

In the implementation of PjBL in STEM, teachers act as facilitators who guide students through various stages of the project. This process usually begins with identifying a problem or challenge that must be solved. After that, students conduct research, design solutions, conduct experiments, and evaluate the results obtained. With a structured project, students are encouraged to work independently or in groups which ultimately improves students' collaboration and responsibility skills.

Project-based learning in STEM also provides a more in-depth learning experience compared to conventional learning methods. In projects involving design and experimentation, students can develop complex problem-solving skills and systematic thinking. In addition, collaborative projects strengthen communication and coordination skills that are very important in the professional world. However, the implementation of PBL in STEM also has its own challenges. One of them is the need for careful planning and the availability of adequate resources. Teachers must have the skills to design projects that are in accordance with the curriculum and are able to provide effective direction to students. In addition, limited facilities and time are often obstacles in implementing projects, especially in schools with limited resources. Therefore, support from schools, government, and the community is very important in ensuring the success of project-based learning in STEM. Overall, PjBL in STEM is an effective approach in increasing student engagement and enriching the learning experience. By providing real challenges and encouraging active exploration, this approach helps students develop 21st-century skills that are much needed in the workplace and everyday life. Despite the challenges in its implementation, the benefits gained are far greater, making PBL a viable strategy to be applied in STEM education at various levels.

Technologies to Support PjBL in STEM

Project-based learning in STEM (Science, Technology, Engineering, and Mathematics) education is increasingly developing with the support of technology. Technology allows the learning process to be more interactive, efficient, and relevant to the real world. By utilizing technology, students can explore STEM concepts in more depth and apply them in complex, data-driven projects. One of the technologies that supports PjBL in STEM is modeling and simulation software. Applications such as PhET Interactive Simulations, Tinkercad, and GeoGebra allow students to conduct virtual experiments before applying them in real projects. For example, in an earthquake-resistant building engineering project, students can use structural modeling software to test their designs before building them in physical form. These simulations not only save costs and time but also provide deeper insights into the underlying scientific principles.

In addition, robotics and programming technologies play a significant role in STEM-based PjBL. Using platforms such as Arduino, Raspberry Pi, or LEGO Mindstorms, students can design and build automation solutions for real-world challenges. For example, in a disaster mitigation project, students can create a sensor-based early warning system that detects environmental changes such as rising water levels.

Augmented Reality (AR) and Virtual Reality (VR) technologies also offer a more immersive learning experience in PjBL. With AR and VR, students can explore 3D models of atomic structures, human anatomy, or even explore outer space environments without having to leave the classroom. Applications such as Merge Cube and Google Expeditions allow students to interact directly with virtual objects in projects, increasing conceptual understanding and engagement in learning.

Although technology offers many benefits in supporting PjBL in STEM, challenges in its use remain. Not all schools have equal access to sophisticated technological devices and training is needed for teachers to be able to utilize technology optimally in learning. Therefore, support from the government and educational institutions is needed to ensure that technology can be well integrated into PjBL STEM at various levels of education. Technology plays a very important role in increasing the effectiveness of PjBL in STEM. By utilizing simulation software, robotics, AI, AR/VR, and online learning platforms, students can develop 21st-century skills such as problem solving, critical thinking, and collaboration. Therefore, the integration of technology in PjBL must continue to be improved so that STEM learning is increasingly relevant to the development of the times and the needs of future industries.

Evaluation and Assessment in Technology-Based STEM Learning

Evaluation and assessment in technology-based STEM (Science, Technology, Engineering, and Mathematics) learning have an important role in measuring student achievement and the effectiveness of the learning process. In STEM learning that emphasizes the application of science in solving real problems, evaluation does not only focus on the final results, but also on students' thinking processes, creativity, and collaboration skills. With the support of technology, assessments can be carried out more interactively, objectively, and data-based to provide more accurate feedback to students and teachers.

One form of assessment commonly used in technology-based STEM learning is project-based assessment. In this method, students are assessed based on their ability to design and complete projects that combine STEM concepts such as robotic modeling, programming-based application development, or data-based scientific experiments. Teachers can use digital assessment rubrics that cover various aspects such as problem solving, innovation, application of theory, and teamwork. By using online learning platforms such as Google Classroom, teachers can collect and evaluate student projects more systematically.

In addition to project-based assessments, technology also enables real-time formative assessments. Tools like Kahoot!, Quizizz, and Socrative allow teachers to give interactive quizzes that provide immediate feedback to students. With the data analytics features available on these platforms, teachers can see patterns in student understanding, identify where students are struggling, and adjust learning strategies to be more effective. With immediate feedback, students can immediately correct mistakes and improve their understanding of the STEM concepts they are learning.

Technology also enables the implementation of simulation-based assessments and virtual experiments. With software such as PhET Interactive Simulations, Tinkercad, or Labster, students can conduct experiments and explore STEM concepts without having to be in a physical laboratory. These simulations not only increase the accessibility of learning but also allow teachers to assess student understanding through the analysis of experimental data that students conduct. For example, in physics learning, students can use simulation applications to test Newton's laws under various conditions and report the results in the form of data-based analysis.

Digital portfolio-based assessment is also an effective approach in technology-based STEM learning. Using platforms such as Google Sites, Seesaw, or Padlet, students can collect and document their work in the form of digital reports, programming codes, or video presentations. These portfolios allow teachers to assess student progress more comprehensively and provide more detailed feedback. In addition, students can also reflect on their learning and develop communication skills by compiling digital reports or presentations.

Although technology provides various advantages in STEM evaluation and assessment, there are several challenges that need to be overcome. One of them is limited access to technological devices in some schools which can cause gaps in the implementation of technology-based assessments. In addition, teachers need to have skills in using various digital tools in order to design assessments that are effective and in accordance with learning objectives. Therefore, training for educators and the provision of adequate technological infrastructure are very important to ensure that evaluation in STEM learning can run optimally. Evaluation and assessment in technology-based STEM learning provide many benefits in increasing the effectiveness of learning and developing student skills. By combining various methods such as project-based assessments, interactive quizzes, digital simulations, and electronic portfolios, educators can assess students' understanding more accurately and deeply. With the support of the right technology, STEM learning can be more adaptive, innovative, and relevant to the needs of the industrial world and future challenges.

Examples of Implementation of PjBL in STEM

Project-Based Learning (PjBL) in STEM (Science, Technology, Engineering, and Mathematics) education provides a more meaningful learning experience by connecting theory and practice in real-world contexts. This method not only improves students' understanding of STEM concepts, but also develops critical thinking skills, problem solving, creativity, and teamwork. The implementation of PjBL in STEM can be done through various projects that are relevant to everyday life and global challenges.

One example of the implementation of PjBL in STEM is the project of designing and building an eco-friendly house model. In this project, students are invited to identify problems related to energy efficiency and environmental sustainability. Students then design a house using the principles of physics in natural lighting, air ventilation, and the use of solar panels as an alternative energy source. In the technology and engineering stage, students can use modeling software such as Tinkercad or SketchUp to create a 3D design of the house. In addition, students can conduct experiments using temperature and light sensors to test the effectiveness of the design created. This project integrates various disciplines in STEM, from science in understanding the concept of energy, technology in the use of modeling software, engineering in model construction, to mathematics in calculating energy efficiency.

Another project that is often implemented in STEM PjBL is the creation of a simple water filtration system. In this project, students are given the challenge of designing and building a water filter that can remove impurities from contaminated water. Students need to understand the science concepts of the physical and chemical properties of water, the technology in selecting effective filter materials, and the engineering in designing an optimal filtration system. Students can also measure the effectiveness of the system they create using water quality sensors or conducting simple laboratory tests. With this project, students not only understand the importance of sanitation and clean water access, but also learn how to apply STEM concepts to solve real-world problems.

Implementation of PjBL in STEM can also be done in the field of robotics and programming. For example, students can be given the challenge of creating a simple robot that can help with household chores or support disaster mitigation. Using platforms such as Arduino or LEGO Mindstorms, students learn to design and program robots so that they can run automatically. This project allows students to understand the principles of electronics, logic-based programming, and mechanical design in one integrated project. In addition, students can conduct tests to improve the performance of the robots they create so that students can develop deeper analytical and problem-solving skills.

In addition to these projects, PjBL in STEM can also be applied in the environmental field using technology such as air quality monitoring using IoT (Internet of Things) sensors. In this project, students can develop a simple tool that can detect air pollution levels and send data in real time to a digital platform. By understanding how sensors, IoT networks, and data analysis work, students can gain further insight into the impacts of air pollution and find technology-based solutions to overcome them. Although PjBL in STEM provides many benefits, its implementation still requires careful planning. Teachers must design projects that are in line with the curriculum and ensure that students have access to the necessary resources. In addition, collaboration with industry or communities can increase the relevance of the project and provide students with broader insights. With the right approach, PjBL in STEM can be an effective learning strategy in equipping students with 21st-century skills and preparing students to face future challenges.

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Chapter 5

STEM Education and Measurement, Evaluation and Feedback Processes

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Chapter Highlights

This section highlights key principles, challenges, and innovative frameworks shaping assessment practices in STEM education, with a focus on equity, feedback, and 21st-century skills.

- Assessment in STEM education must shift from typical testing to include a broad range of diagnostic, formative, and summative strategies. They must assess high-level, interdisciplinary skills like critical thinking, collaboration, and applied problem-solving.
- Good feedback is a cornerstone of excellent STEM education. Where timely, specific, and growth-oriented, feedback empowers learners, supports self-regulation, and allows the iterative cycle of inquiry and design that underpins learning in STEM subjects.
- Inclusive STEM Assessment Framework (ISAF) is presented as an integrated framework in response to significant challenges. Its four pillars—Multi-Modal Measurement, Culturally Responsive Evaluation, Dynamic Assessment, and Empowering Feedback—work together to facilitate equitable and rigorous assessment practices.
- Some of the major STEM assessment challenges include interdisciplinary complexity, ensuring reliability and validity for non-traditional activities, teacher assessment literacy, and creating inclusive measures that are equitable for diverse student populations.

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Introduction

As countries struggle with technology problems and knowledge economy transformations, an increasing consensus is that we need STEM-literate citizens. STEM education, however, is much more than just teaching the STEM subjects. Our STEM vision is really more of a transdisciplinary and transferable environment for developing the critical, creative, and problem-solving skills needed to propel society forward (Rosenberg et al., 2018). Education systems worldwide are therefore redefining curriculum in order to become comprehensive STEM experiences that integrate theory with practice and allow students to prepare to navigate complex real-world problem spaces (English, 2016).

This does not mean that the revolutionizing potential of STEM education itself is flawed because, in fact, it is, particularly with regard to measurement. The mean by which measuring, evaluation, and giving feedback occur is perhaps the most vital process that will deliver quality and equity in STEM teaching and education. These procedures will provide evidence of what students can do to affect teaching and curriculum planning, and for helping students reflect upon and build their own performance (Black & Wiliam, 2009). Rather than the traditional, summative assessment and testing view of assessment, emergent models have placed emphasis on formative assessments that help support learners developing deeper learning, self-regulation, and continuous improvement.

Measurement in education is the process of quantifying the knowledge, skills or attitudes that students have systematic processes (Brookhart & Nitko, 2019); evaluation is the process of making value judgments about the quality or effectiveness of the teaching and learning based on measured data (Guskey, 2016). Feedback is information provided to students to facilitate future learning (Hattie & Timperley, 2007); performance assessment involves learners demonstrating skills, or creating products that represent true-to-life, real-world tasks (Darling-Hammond, 2014). Alternative measures are constructed to capture a fuller picture of learning, with an emphasis on creativity, collaboration, and problem-solving besides standardized testing (Torrance, 2012). Theese are the foundations of a diverse and rich assessment culture in STEM education.

On an international scale, STEM measurement and assessment is one of the priorities in OECD and UNESCO agendas committing to, accountability, lifelong learning, and equity (OECD, 2019; UNESCO, 2017). Measurement and assessment does not only imply endpoints are being measured; they are processes with scaffolds for the measurement of change to build a knowledge economy that fosters innovation, competitiveness, and social inclusion. STEM assessment and evaluation are related to system change, responsibility, and equity in learning. They serve to identify areas of growth beyond absolute measures, enable international comparability, and guide curriculum reform. Measurement is in quantitative forms and as assessment, measure provides context for areas of growth and therefore use attention for formative and summative assessment activity that can lead to instructional improvement quality (Brookhart & Nitko, 2019). STEM measurement and evaluation are more grounded on lesser pure positivist and more on those that emphasize engagement, equity, and identity that call for the importance of knowledge-construction (Abedi, 2010). Computerization of some of the educational accountability measures provides real-time monitoring and quality measure experience for the students. In addition to traditional relative or absolute assessments, large-scale national and international benchmark assessments now use adaptive testing and learning analytics to deliver personalized, multimodal feedback through real-time, authentic digital evaluation (Ifenthaler & Yau, 2020).

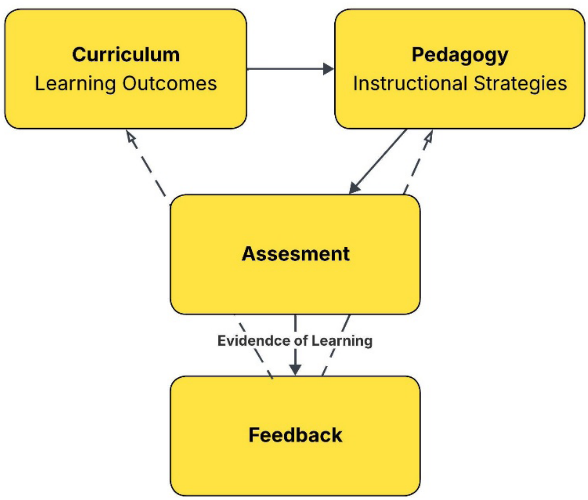

Figure 1. The Curriculum-Pedagogy-Assessment Cycle

Evaluation and assessment offer vital data for shaping policy, allocating resources, and ensuring institutional accountability (Stiggins, 2014). When combined with culturally responsive practices, these processes foster inclusivity by acknowledging and integrating diverse knowledge systems and forms of representation (Gay, 2018). Curriculum, pedagogy, and assessment are inherently functional and cyclical (Figure 1): The curriculum lays out the intended learning outcomes, pedagogy determines the processes and strategies employed to deliver the lesson, and assessment provides credible evidence used for reflection and evidence to inform/enhance the curriculum and pedagogy. Feedback and the cyclical nature of the three elements ensures that assessment is not simply a phase added onto and is intrinsic to teaching and student success.

Measurement and Evaluation Types, Strategies, Methods, and Techniques

In STEM education, assessment extends far beyond traditional testing to encompass a diverse array of evaluation and measurement methods tailored to interdisciplinary, skills-oriented learning. These approaches are designed not only to measure outcomes but also to actively support the development of critical thinking, collaboration, creativity, and problem-solving skills. Because STEM education emphasizes authentic, inquiry-based experiences, assessment must similarly evolve to capture complex competencies through both formative and summative strategies. The following section and Table 1 (Adapted from (Black & Wiliam, 1998; Brookhart, 2017; Bybee, 2013; Popham, 2009; Stiggins, 2014) present key assessment methods, including their definitions, advantages, limitations, and practical examples, to assist educators in designing meaningful, research-informed evaluations that align with contemporary STEM learning goals.

Diagnostic Assessment

Diagnostic assessment focuses on mapping students' prior knowledge and misconceptions, as delineated in Table 1. This preventative assessment can then better inform the pedagogy of practitioners, as they know precisely what manner of teaching practice can fill the gaps and what prior knowledge can be built on (Brookhart & Nitko, 2019). Pre-tests are a clear example as they give a quantitative picture of where a student is at in specific prerequisite skills - i.e., for a calculus unit, an algebra pre-test identifying the gaps in knowledge. Whereas concept maps develop a qualitative understanding of the student, as to how they have structured their own cognition, and how they have laid out the connection between ideas within a discipline, for instance, producing a concept map for parts of the human nervous system before studying in-depth it (Novak & Cañas, 2008). While being valuable for developing individualized learning pathways, Table 1 also appropriately points out the weaknesses: A pre-test may not predict future performance,

Table 1. Measurement and Evaluation Types, Methods, Advantages, Disadvantages and Examples

Type	Method / Tool	Definition	Advantages	Disadvantages	Example in STEM
Diagnostic	Pre-Test	Pre-assessments to identify prior knowledge or misconceptions before instruction.	Tailors instruction to student needs; prevents learning gaps.	May not predict future performance; time-intensive to design.	A pre-test on algebraic functions in a calculus class to identify gaps before teaching derivatives.
	Concept Map	A visual diagram that illustrates the relationships between concepts and ideas, often represented in a hierarchical structure with connecting lines and linking words.	Effectively evaluate a student's comprehensive knowledge structure, uncover hidden misunderstandings, and directly assess critical analytical and synthesis skills.	The assessment is often labor-intensive and subjective, requires significant time for large groups, and demands prior student training to be effective.	Mapping the human nervous system. Students create a map linking central concepts (Central Nervous System, Peripheral Nervous System) to sub-concepts (neurons, brain, spinal cord, senses) with labelled connections (e.g., "contains", "sends signals to").
Summative	Standardized Testing	Uniform tests to measure STEM proficiency across populations.	Comparable across contexts; aligns with standards.	May not capture interdisciplinary skills; risk of teaching to the test.	An AP Computer Science exam assessing coding and debugging skills.
	Lab Report	Assessing student achievement at the end of a unit or a course to determine mastery of objectives.	Measures overall competency; useful for grading and certification; aligns with standards.	Limited feedback for improvement; may not capture learning process.	A final physics lab report analyzing pendulum motion to evaluate understanding of harmonic motion.
	Project-Based Assessment	Tasks requiring students to integrate STEM knowledge in real-world projects.	Mirrors real-world applications; fosters collaboration and problem-solving.	Resource-intensive; subjective scoring without clear rubrics.	Designing a model bridge in an engineering class, assessed via rubric for design and teamwork.

Summative	Performance-Based Assessment	Hands-on tasks demonstrating practical STEM skills.	Assesses application of knowledge; authentic to STEM practices.	Time-consuming; requires clear criteria to avoid bias.	Conducting a titration experiment in chemistry to demonstrate lab techniques and data analysis.
	Portfolio	Collecting student work over time to show growth and competencies.	Captures long-term progress; interdisciplinary focus.	Time-intensive to compile and assess; requires clear evaluation criteria.	A robotics portfolio including code iterations and prototype designs to show skill development.
Formative	Clicker Questions	Ongoing assessments during instruction to provide feedback and guide teaching adjustments.	Enhances student engagement; allows real-time instructional changes; fosters learning growth.	Time-consuming; requires teacher expertise to implement effectively.	Using clicker questions in a biology class to assess understanding of ecosystems and adjust the lesson.
	Observation	Capturing non-numerical data through observations, reflections, or portfolios to assess processes and attitudes.	Offers deep insights into complex STEM skills; supports interdisciplinary assessment.	Subjective; time-intensive to analyze; less standardized.	Evaluating design journals in an engineering project to assess students' problem-solving process.
	Peer and Self Assessment	Students evaluating their own or peers' work to foster metacognition.	Promotes reflection and accountability; enhances student engagement.	Subjective; requires training for reliability.	Peer review of contributions in a group solar-powered car project.
	Technology-Enhanced Assessment	Using digital tools like simulations for dynamic evaluation.	Engages students; mirrors real-world STEM tools; provides instant feedback.	Requires technology access; potential equity issues.	A PhET simulation assessing physics concepts through virtual pendulum experiments.

Formative	Rubric	A scoring guide that uses specific pre-defined criteria to evaluate student work, with detailed descriptions of performance levels for each criterion.	Enhances grading fairness, provide clear feedback, clarify goals, and streamline the evaluation process.	The development requires significant time, they can stifle creativity, and overly strict criteria may hinder a holistic assessment.	Evaluating a lab report. Criteria include Hypothesis, Methodology, Data Analysis, Conclusions, and Safety. Each has performance levels (e.g., Novice, Proficient, Exemplary) with clear descriptors.
	Rating Scale	An assessment tool that uses a set of categories designed to measure the degree to which a behavior, attitude, or skill is present or performed.	Efficient to use, effectively assess observable behaviors and attitudes, and provide quantifiable data for progress monitoring.	They are susceptible to rater bias, offer little constructive feedback, and can suffer from inconsistent interpretation among evaluators.	Assessing collaboration in a robotics project. A scale from 1 (Rarely) to 5 (Always) is used to rate behaviors like "Shares ideas effectively," "Listens to team members," and "Completes assigned tasks on time."
Program Evaluation	Data Analysis	Judging program or curriculum effectiveness using aggregated data.	Informs systemic improvements; supports accountability.	Broad focus may overlook individual needs; requires robust data collection.	Analyzing student performance in a robotics curriculum to evaluate program effectiveness.

or analyzing concept maps may take too much time and be too subjective that students (and teachers) may not be able to be educated effectively.

Summative Assessment

Summative assessment, which involves measuring student achievement at the end of a period of learning, has a range of methods that certify mastery and include accountability data (Pellegrino et al., 2001). Summative assessment in STEM instruction is very different from simply giving students a final exam. As can be seen in Table 1, summative assessments include a variety of authentic assessments that address the integrated nature of STEM. Similarly, standardized tests (e.g., AP Computer Science exams) afford reliable, comparable data across populations, but also run the risk of missing interdisciplinary application and the promotion of "teaching to the test" (Koretz, 2017). Performance assessments and project-based assessments are the best forms of summative assessment to measure students' application of knowledge and real-world skills (Darling-Hammond, 2014). Additionally, portfolios offer a more complete and qualitative picture of long-term growth and competency development by including selections of work over time (Barrett, 2007), such as iterations of code and design documents from a robotics class. Although these techniques present a fuller picture of learning, these techniques require resources and rely on well-defined rubrics to support consistent and objective scoring (Panadero & Jonsson, 213). These methods consider not just the final product, but also the strength of the inquiry and collaboration.

Formative Assessment

Formative assessment consists of a set of continuous assessment strategies as described in Table 1 that are designed to occur during instruction and offer immediate feedback, allowing for modifications in instruction (Black & Wiliam, 2009). In STEM education, they especially help students continuously grow their conceptual understanding. There are a number of ways to gain timely and flexible information about students ' developing ideas. Clicker questions and other technology-based assessments (PhET, etc.) offer quick feedback to check for understanding and make adjustments to teaching in real-time (Shute & Rahimi, 2017). More qualitatively, allowing students to show their work during the processes, and involving students' peers in self-assessments or peer assessments, introduce incentive toward metacognition, accountability and developing collaborative skills (Topping, 2010) which are critical skills for STEM practices. Some rubrics and rating scales are very formative in nature and almost more structure and less standards to clarify the goals and expectations of students and simplify the evaluation of work done for students. Nevertheless, while Table 1 addresses the importance of teacher knowledge to carry out these methods effectively, they also can present significant time demands. In inquiry-based STEM classroom settings, these formative assessments are vital to making decisions effectively about the next instructional action, permitting time for self-regulation, and investigating deeper problem-solving (Heritage, 2022).

Program Evaluation

Program evaluation verifies how well a program or curriculum functions by utilizing hyphenated data as the central focus, as indicated in Table 1 by the method of data analysis (Popham 2009). Although evaluative assessment considers the individual learners' outcomes of learning to guide decision-making at a bigger scale, it principally synthesizes outcomes and assists in making intelligent decisions about policies, the use of resources, and upgrades. The analysis of how data occurs is the central method through which evaluative assessment occurs through tallying and observation of aggregated data through numerous sources. The quantitative analysis examines data gathered as student performance measures and examined collectively. The key advantage is that it may bring about change at the whole system level and hold individuals accountable. Validity questions are significant when numerous sources and systems are needed to gather and report credible data (Madaus et al., 1983). Ultimately, evaluative assessment assembles significant evidence to respond to questions such as, "Is our STEM program accomplishing its objectives?"

Alternative Assessment

In the case of STEM, alternate assessment can reveal what students know and how students learn that cannot be revealed by regular testing. It measures real-world skills, how students do what they do, and how they experience something. The issue of whether or not to treat "Alternative Assessment" as a category is a complicated one. In contemporary literature about assessment, it is an umbrella term that includes any assessment that is an alternative to traditional standardized testing and multiple-choice exams. In this sense, most, if not all, in the list of methods from Table 1, such as project-based assessments, portfolios, concept maps, peer review, etc., would fall under the umbrella of alternative assessment. They are considered "alternative" because they provide a fuller, authentic picture of learning instead of focusing primarily on rote memorization, by valuing process, creativity, and application (Darling-Hammond, 2014).

In summary, diagnostic assessments, conducted before or at the start of instruction, reveal students' existing knowledge, misunderstandings, and readiness (Brookhart & Nitko, 2019). A math pretest before an engineering project, for instance, may inform interventions, while algebra diagnostic assessments before robotics operations help group learners based on their skills. These types of assessments not only offer quantitative results but also have qualitative elements, such as teamwork, equivalence problem identification, and developmental benefit based on Vygotsky's Zone of Proximal Development. Their contemporaneous nature makes them downright crucial in preparing students whenever formative or summative assessments are not available.

Mixed methods combined measurement also strengthens measurement, since cognitive, procedural, and affective learning can be best understood by more than one approach. Quantitative measures such as rubric scores and accuracy checks and qualitative measures such as reflective journals and field notes provide richer accounts of learning without overwhelming the assessment design. Interdisciplinary projects benefit the most, since both process dynamics and product quality are measured. In science, for example, laboratory notebooks qualitatively log hypotheses, while experiments are quantitatively measured. In technology, testing automatically verifies coding correctness, while peer reviews gauge creativity, elegance, and efficiency. By blending performance-based and reflective data, mixed methods more equally balance correctness and style.

Innovative Tools and Technological Applications to Support Assessment

Digital tools enhance STEM assessment through immediate data collection, adaptive feedback, and multimodal representation of learning. Typical tools include digital rubrics, electronic portfolios, and learning analytics. Digital rubrics, integrated via learning management systems or designated software, make it possible to conduct targeted assessment, take notes, monitor progress, and report to parents and students (Marzano, 2006). Multimedia-capable e-portfolios showcase STEM competencies in evidence-based form, while learning analytics quantify engagement through tracking variables like simulation use, correctness of problem-solving, and task duration of engagement (Long & Siemens, 2014). These technologies support teachers' decisions on scaffolding and differentiation based on data. Application-based assessments extend these possibilities through mobile apps for fieldwork, coding apps with debugging diagnostics, and simulation software for iterative design (Blikstein, 2013). Resources such as Tinkercad and Scratch demonstrate this by enabling computation modeling and also providing teachers with an idea of design iteration and problem-solving exercises.

Feedback Mechanisms in STEM Education

Feedback is an essential strategy that not only assesses student work but actively develops and builds learning in education. As STEM learning environments move toward more process than product, creativity than compliance, and inquiry than instruction, feedback emerges as a dynamic process negotiating instruction and metacognition (Hattie & Timperley, 2007). In contrast to summative evaluation, feedback, when prompt, personalized, and constructive, assists learners as they progress through experimental cycles of failing, reflecting, and revising.

A number of interrelated attributes characterizes good feedback: Timeliness, specificity, clarity, and personalization. Feedback is best delivered in real time or as soon as possible so that students can relate the information to the activity being undertaken and correct it in the process (Shute, 2008). In STEM classrooms, feedback allows students to explore their way through iterative refinement (Brookhart, 2017). Clarity and constructive language must also be present. “Correct” or “incorrect” is sometimes all that differentiates the feedback provided on an outcome. However, students do recognize diagnostic feedback as quality assessment that systematically signals strengths, weaknesses, and specific follow-up actions (Wiliam, 2011). Finally, feedback is also most helpful for promoting longer-term achievement and motivation when it is personalized to the student at hand, perhaps in regards to variation in their growth or learning, or in regards to an aspect of conceptual misunderstanding (Nicol & Macfarlane-Dick, 2006).

The Influence of Feedback on Learning

Feedback is part of STEM pedagogy for deep learning, if even in regards to the how and why of students’ work, not just the what. Feedback is the number one single school level factor that can influence student outcomes according to Hattie’s (2008) meta-meta-analysis study. In non-negotiable linear teaching and learning characteristics in STEM settings, perhaps more than any other discipline or degree of academia, learning is literally most of the time a linear experience of needing to work through ignorance, and conceptualizing what they thought they knew in terms of evidence-based experimentation.

Feedback also generated in the service of a mastery climate can overcome the test anxieties and the competitive nature of STEM culture. Feedback facilitates students' self-regulated learning by helping to apply criteria for assessments to the monitoring of one's own performance (Zimmerman & Schunk, 2001). With reflection, goal setting, and discussion that activates a sense of responsibility for learning, feedback can help learners take responsibility for the process of learning. Through role modeling of metacognition and soliciting students' feedback practices, teachers form a routine of self-regulation. Self-regulation supports include reflection diaries and self-assessment checklists that help students identify areas of weakness and work towards developing an improvement plan. These self-regulatory methods aid in the area of STEM, where achievement is usually contingent on planning, monitoring, and revision of procedures (Nicol, 2010).

Placing the Student at the Center of the Assessment Process

The main objective of feedback is to develop student autonomy, which is achieved by making students responsible for their learning (Nicol & Macfarlane-Dick, 2006). For this, students must move from being passive consumers of assessment to active participants in assessments. As well as its value, what matters is how feedback is perceived and acted upon (Carless & Boud, 2018). The efficacy of feedback can also depend on a student's mindset, receptiveness to criticism, and commitment to their goals. In addition, developing student "assessment literacy" has been shown to help students understand criteria, understand where they are and where they want to be, and act on feedback. Teachers can promote assessment literacy by using self-assessment, self-reflection, and peer-assessment and develop feedback as a guide to learning rather than assigning a grade.

Real-Time and Continuous Feedback Approaches in STEM Education

Because of the process-based nature of STEM learning, feedback is often needed to be continuous and embedded within instruction. Real-time feedback can provide immediate cognitive redirection without disrupting the flow of engagement (Ruiz-Primo & Furtak, 2007). Technology-enhanced formative assessment tools like learning management systems, computer simulations, and data dashboards enable educators to offer personalized feedback in a convenient way. For example, web-based applications like Desmos, PhET simulations, or Tinkercad allow teachers to track student work and provide context-specific intervention (Blikstein, 2013). Not only do these sites enable feedback, but they also record rich data that inform instruction. Audio or video comments can be used to personalize responses in STEM project works, particularly in evaluating multimedia portfolios or explaining nuanced errors in technical work. It can enhance class engagement and provide a more personalized teaching presence, especially for blended or online STEM education (Mahoney et al., 2019).

Examples of Teacher, Peer, and Student Feedback in STEM

Feedback in STEM education occurs in many different formats. Teacher feedback may take the form of a mini-conference, written comments on a lab report, or a project graded with a rubric that reflects expectations and practices within the discipline. Peer feedback applies the principles of social learning. While some feedback processes are informal, e.g., "two stars and a wish," there are structured ways to provide peer feedback, e.g., "TAG: Tell something you like, Ask a question, Give a suggestion." Structured feedback opportunities encourage students to develop critical evaluation skills while building a community of learners that responds to feedback (Topping, 2010).

Table 2. Examples of Effective and Ineffective Feedback in STEM

Context	Ineffective Feedback	Effective Feedback
Lab Report	"Your analysis is weak."	"Accurate data collection. Connect your findings to chemical equilibrium from Chapter 3 to strengthen conclusions."
Coding Project	"Your code is messy."	"Program runs correctly. Improve readability with comments and descriptive variable names."
Engineering Prototype	"This design won't work."	"The single beam buckled-consider using triangular supports to distribute load and improve stability."
Solar System Model	"Your planets are out of order."	"Your model is very creative! For better accuracy, remember the acronym 'My Very Educated Mother Just Served Us Noodles' to recall the planet order."
Paper Bridge Project	"This isn't strong enough."	"Great start on your paper bridge! To hold more weight, try folding the paper into a U-shape or a tube to make a stronger beam."

Self-feedback encourages metacognition, and allows students to self-reflect using goal-setting worksheets, reflection journals, or analyzing errors. Each of these means requires students to identify strengths and weaknesses, analyze the cause of any weaknesses, and make plans for improvement. Self-feedback develops the metacognitive skills required of students in a cyclical STEM process. Table 2 provides some examples of effective vs. ineffective feedback in STEM.

Evaluation and Assessment Models and Best Practices Globally

STEM education utilizes various ways of assessment, feedback, and measurements based on national contexts, policies, and cultures (OECD, 2020). These distinctions provide adaptable models and generic principles for local reform (Breakspear, 2012). Table 3 portrays how some countries balance centrally mandated examinations with student-centered approaches that include the agency of teachers. An example of a student-centered model is Finland, which has very little national standardized testing, and uses mostly formative assessment (Sahlberg, 2021). South Korea has a similar history of examinations and with various reforms now encourages project-based learning by mandating that schools engage in creative experiential activities (Hong, 2021). In the United States, a federal system promotes high degrees of variability amongst states, especially in light of the broad framework for multidimensional assessment offered by the Next Generation Science Standards (NGSS), which most states have not adopted (NGSS Lead States, 2013).

Global assessments, such as PISA and TIMSS, signify quality in STEM education and provide benchmarks for policy-making and reform based on applied knowledge and curriculum-based achievement (OECD, 2019; Breakspear, 2012). Effective evaluation systems extend well beyond the classroom to professional development and teacher education (OECD, 2020). Finland has included evaluation literacy within their teacher education (Sahlberg, 2021) and South Korea invests in high-quality professional development which may facilitate schools (Hong, 2021). Overall, these examples indicate that for the objectives of equity and quality in STEM evaluation to be realized there must be coherence across policy, practice, and pedagogy (OECD, 2020). International models can be comparatively summed up in a table as follows:

Table 3. Comparative Approaches to STEM Assessment

Country	Dominant Strategies	Key Challenges	Outcomes/ Strengths
United States	NGSS-aligned performance tasks; rubrics	Local variability; equity gaps	Innovation, diverse practices
Finland	Formative, portfolio-based	Limited comparability across systems	Strong teacher autonomy, equity focus
South Korea	Exams + creative experiential activities	Transitioning from exam-heavy culture	High achievement, gradual shift to innovation
Singapore	Inquiry-based, high-stakes integrated	Pressure from exams; teacher workload	Strong international performance
Canada	Competency-based, inclusive assessments	Provincial variability	Equity-oriented and culturally responsive
Australia	National curriculum, digital tools	Balancing standardization vs. innovation	Strong integration of ICT in assessment

At the system level, STEM national assessment policy is incorporated into education reform and teacher development agendas overall. As a case in point, in South Korea, continuous professional development of STEM teachers involves specialized training for designing and deploying assessment instruments. Finland puts emphasis on assessment literacy as part of initial teacher training, encouraging theoretical and practical competencies in non-traditional modes of assessment (OECD, 2020). Private funding initiatives as well as public policies in the United States enable the implementation of school-level STEM testing systems with a particular focus on genuine, inquiry-based assessment practices (Honey et al., 2014).

All these global models collectively highlight the pressing need for aligning macro-level policy decisions with the development of institutional capacity and classroom-level instructional designs. The US example highlights the federal policy provincials' importance in fashioning locally-grounded innovation; the Finnish example offers a powerful vision of teacher-directed, trust-based systems of assessment; and South Korea illustrates how top-down policy reforms can stimulate teaching innovation in the face of systemic constraints. Overall, these examples highlight the importance of policy, pedagogy, and practice coherence in the pursuit of equitable, high-quality STEM assessment.

Hattie and Timperley's (2007) highly applied model provides an organized method for learning feedback. Their "three questions" approach—Where am I going? How am I going? Where to next?—provides clarity on learning goals, presents evidence of journeying, and plots courses for future development. Translated to STEM contexts, feedback can assist with mathematics iterations of hypothesis construction, prototyping, and refinement.

It also must be distinguished from formative and summative feedback. Formative feedback is provided during learning and is designed to improve processes, while summative feedback is typically backward-looking, presenting evaluative judgments following completion of tasks (Heritage, 2022). Formative feedback is especially critical in STEM because of the trial-and-error nature of scientific discovery and design. Finally, cultural influences shape the perception and perception of feedback. Feedback in East Asian environments is indirect, embedded in shared performance expectations, while Western cultures emphasize direct, individualized comments. Accounting for these kinds of cultural variations is essential while developing feedback systems for more globalized and diverse STEM classrooms.

Challenges in Measurement and Evaluation within STEM Education

STEM education, given its interdisciplinary nature, practice-based learning methods, and focus on higher-order thinking abilities, presents challenges to the field of assessment and evaluation (Honey et al., 2014). This subsection will explain the origins of issues surrounding the issue of assessment and evaluation in STEM education, followed by educational practice implications.

Interdisciplinary Complexities

STEM education links science, mathematics, technology, and engineering as one learning framework, even though the disciplines have different epistemologies, knowledge building practices, and assessments in isolation. Interdisciplinary assessments are challenging to develop, as there are notable differences for assessment such as assessing the engineering design process as opposed to mathematical problem solving. Integrated rubrics are necessary to assess however, both discipline-specific competency and transdisciplinary competency like problem solving and collaboration. This type of assessment will account for the diverse and complex learning and STEM related outcomes that may develop within interdisciplinary projects by assessing how knowledge has been used across multiple fields. This approach will provide a clear way to assess and measure STEM learning outcomes.

Objectivity, Reliability, Validity Issues

In STEM assessments, open-response items and project-based learning are prone to subjectivity as there is often no clear correlation to the learning objectives (Mohommadi et al., 2022). Rubrics serve to increase reliability but there are few STEM specific rubrics that could threaten validity, especially with respect to emergent outcomes like creativity or collaboration. Collaboratively working with teachers to co-construct rubrics, calibrate against exemplars, or moderation sessions can increase reliability and assist with subjectivity. Collectively, they would improve the objectivity and validity of STEM assessment.

Teacher Competence and the Limitations of Assessment Tools

The pedagogical skill of STEM instructors in assessment and evaluation is crucial to the process's effectiveness. However, the majority of teachers, particularly when handling project or process-based assessments, report insufficient knowledge and training in measurement techniques (Plake & Impara, 1996). This shortage incapacitates them both in the production of quality instruments as well as in justifiably interpreting the results of their tests. Moreover, none of the current tools is holistic enough to encompass interdisciplinary learning, while none provides a system for tracking students' process of learning (National Research Council, 2011). Thus, this indicates the urgency need for constant, proactive professional development courses for educators that can exemplify the ways to build and score complex performances tasks.

Student Diversity and Inclusive Assessment

New cultural, linguistic, and cognitive diversities of the STEM classrooms demand inclusive measurement (Abedi, 2010). Existing assessment methods and techniques fall short in reflecting the knowledge all students have. In the case of special needs students, immigrant, and LGBTQ students for example, if such students are to be provided accessible and flexible assessments, the assessment will be flexible and provide choices, differentiation, assessment accommodations and continuous monitoring for inclusivity. Schools, staff, and policymakers can collaborate in addressing assessment to serve diverse learners better and to maximize equity in STEM education.

Challenges in Data Analysis and Interpreting Results

Since learning analytics increasingly depend on STEM education, the teacher is not statistical and technological literacy competent enough to play around with data, which may lead to data being interpreted incorrectly and, more importantly, limiting pedagogical potential (Bienkowski et al., 2012). Ethical issues relating to student privacy, student information ownership, and algorithmic bias mean that there need to be sufficient policies in place to ensure accountability, consent, and transparency. High-stakes standardized tests will inevitably focus on surface performances, usually degrading STEM education to accountability rather than authentic creativity. Facilitating some concomitant literacy in assessment will thus require teacher professionalism and social obligation, technology-enabled practice awareness (DeLuca & Klinger, 2010). Artificial intelligence software will enable assessment of high-level STEM products of students, but biased data sets and black box methods--the "black box problem" will ensure that it will render null and void that would impose a commitment to Explainable AI (XAI) for fairness. A normative framework of transparency, justice, autonomy and beneficence will be required for equitable digital STEM assessments

Towards an Inclusive STEM Assessment Framework

The issues explained above reveal that the existing STEM assessment approaches are not productive. Rather than dealing with these matters separately as independent units of concern, we need a framework, which places these concerns altogether in an integrated, adaptable and principle-guided way. This section builds on the idea of system response to such issues and identifies urgency gaps in the profession with an Inclusive STEM Assessment Framework (ISAF). The problems we have outlined can be reframed on the basis of principles for a more equitable and effective assessment system than problems. ISAF, for example, is comprised of a pillar, the "multimodal assessment," which marks a potential to address interdisciplinary complexity and the "Culturally Responsive Assessment" pillar that addresses diversity of students as an asset.

From the gaps and best practice identified in international models (OECD, 2019), the Inclusive STEM Assessment Framework (ISAF) focuses on a commitment to equity and engagement, which is the basis for inclusive education (Ainscow, 2020) and is consequently changing the framework from an assessment tool to a change tool. The ISAF has four interrelated pillars:

Multi-Mode Measurement: This is about going beyond normed tests and application of full range of evidence (multimodal) (Pellegrino et al., 2001). It includes quantitative data (scores, analytics), qualitative data (journals, observation), and participatory data (self/peer-assessment) to collect the full range of student skill, particularly from students who come from various cultural, language, and cognitive backgrounds (Abedi, 2010).

Culturally Responsive Evaluation: Evaluation criteria and rubrics must be co-constructed with students to reflect diverse ways of knowing and problem-solving (Gay, 2018; Ladson-Billings, 1995). This approach aligns with the principles of inclusive education, which advocates for the removal of barriers to participation and learning for all students (Ainscow, 2020). This involves recognizing that 'valid' solutions can be presented in different forms (narrative, graphical, prototype, code) and that context is a critical component of judging quality.

Dynamic Assessment: Assessment is not a singular event but an ongoing, dialogic process integrated into the learning cycle (Black & Wiliam, 2009). This pillar emphasizes diagnostic and formative functions, where assessment is used to scaffold learning in real-time, adapting to the learner's zone of proximal development (Lantolf & Poehner, 2004).

Empowering Feedback: Feedback mechanisms are designed to be timely, specific, and growth-oriented (Shute, 2008). More importantly, they must be accessible and actionable for all learners (Banks, 2016). This involves leveraging technology for personalized pathways and ensuring language and delivery modes (audio, video, text) are tailored to individual learner needs, fostering self-regulation and a growth mindset (Zimmerman & Schunk, 2001). The interconnected and cyclical nature of these four pillars is visualized in Figure 2:

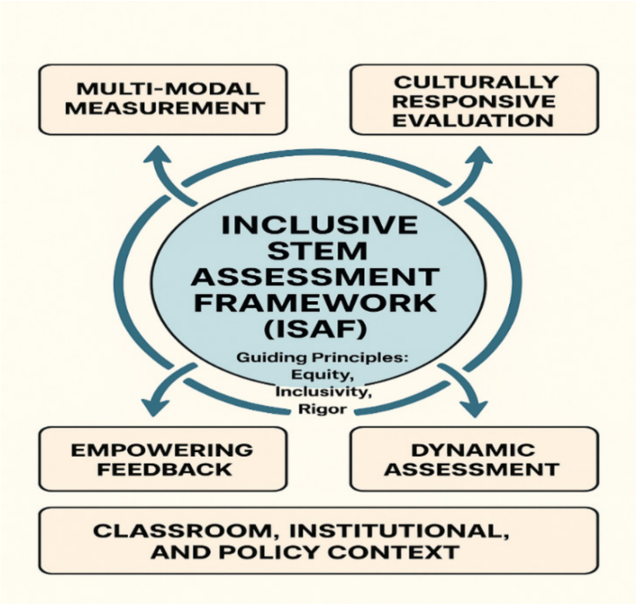

Figure 2. The Inclusive STEM Assessment Framework (ISAF)

The ISAF is a cyclical and dynamic model consisting of four core pillars that interact continuously. The process begins with Multi-Modal Measurement to gather diverse evidence of learning. This evidence is then judged through Culturally Responsive Evaluation based on co-constructed criteria. The evaluation informs Dynamic Assessment, an ongoing process of diagnosis and scaffolding that shapes the learning journey. Throughout this journey, Empowering Feedback is provided to foster growth and self-regulation. The insights from feedback then inform the next cycle of measurement, creating a continuous feedback loop. All pillars are underpinned by the core principles of equity, inclusivity, and rigor, and the framework operates within and is influenced by broader classroom, institutional, and policy contexts.

In this framework, “rigor” refers not only to the difficulty of content knowledge as traditionally understood, but also to the cognitive depth and complexity of skill application (Hess, 2009). ISAF redefines rigor by assessing the extent to which students demonstrate higher-order thinking skills, such as analyzing complex problems, designing creative solutions, synthesizing interdisciplinary knowledge, and constructing evidence-based arguments, rather than simply measuring their capacity to memorize information (Brookhart, 2017). Therefore, this model aims to measure deeper and more authentic learning rigor through multimodal and inclusive methods, as real-world STEM problems are rarely solved with standardized test items that have a single correct answer (Pellegrino & Hilton, 2012). This framework does not prescribe a single tool but advocates for a principle-based approach. It urges educators and policymakers to design assessment systems that are not only rigorous but also inherently equitable, ensuring that every student has the opportunity to demonstrate their STEM literacy in multiple ways (Rosenberg et al., 2018).

Conclusion

In light of the challenges and opportunities examined in this chapter, following concrete steps are suggested for teachers, administrators, and policy makers to transform the culture of assessment in STEM education.

For Teachers: Incorporate simple tech tools by using free platforms like Socrative or Mentimeter for quick formative checks during lessons. Utilize Padlet, Miro, FigJam, Lucidspark, Microsoft Whiteboard, and Canva for collaborative brainstorming and formative feedback on project ideas. Adopt a feedback protocol by implementing structured methods like "Two Stars and a Wish" (for peer feedback) or "What? So What? Now What?" (for self-reflection journals) to make feedback consistent and developmentally focused. Try a digital portfolio by using applications like Google or Seesaw to have students compile their work. This approach supports a complete evaluation of growth and is an easy way to give feedback on the student's artifacts (audio/video).

For Administrators: Prioritize professional development on:

1. Rubric Calibration: The procedure to ensure scoring consistency across teachers.

2. Interpret Learning Analytics: Being able to read dashboards from LMS platforms.

3. Culturally Responsive Assessment: The way in which to implement fair tasks and assessments.

4. Audit Assessment Tools/Software: Once a year audit school software and tools, so your school or district is compliant with student data privacy (FERPA in the United States or GDPR in the EU).

5. Encourage Teacher Collaboration: In order for the PLCs (Professional Learning Communities) to analyze student assessment data and moderate the scoring of student work to ensure reliability and share best practices, allow for dedicated time to work together.

For Policymakers: Create grants for schools to pilot new assessment models. For example, model badges to act as micro-credentials for specific STEM skills and produce competency-based progression models. Mandate, and fund the creation of, clear enforceable ethical guidelines for EdTech procurement to ensure that every tool used in a public school will meet strict standards for data privacy, algorithmic fairness and accessibility. Re-frame accountability metrics by going beyond standardized test scores as the primary measure of school success. Create a balanced dashboard of indicators that include, commonly student engagement in STEM projects, participation in science fairs, and measured growth in portfolios.

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Chapter 6

(Re)Defining Scientific Wealth: Exploring Economic and Sociocultural Currencies in STEM Education

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Chapter Highlights

The following points outline key conceptual perspectives that frame STEM learning through sociocultural and economic lenses, emphasising knowledge exchange, value systems, and the development of students' scientific wealth.

- Exchange of Knowledge – Learners engage in the continual exchange of knowledge and meaning within formal and informal STEM learning spaces.
- Scientific Currencies and Scientific Wealth – In STEM classrooms, learners participate in the exchange of currencies that include language, skills, identity, and culture. I analogize such economic and sociocultural traditions as currencies that circulate within STEM education contexts that ultimately cultivate students' scientific wealth. This metaphor offers an opportunity to reframe traditional notions of the value attached to STEM education
- Economic Motivations for STEM Education – Historical trends indicate that economic motivations – such as national security and global competitiveness – undergird growth of STEM education in the U.S.
- Tenets of Sociocultural Theories – The tenets of sociocultural perspectives reveal valuable modes of currency – such as language, identity, and shared experience – that are under exchange within STEM education spaces that are unaccounted for by economic perspectives alone.

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Introduction

I was in ninth grade when I first felt like a scientist. I had recently joined my junior high school's Science Olympiad team at the encouragement of my favorite teacher – Mrs. K. Founded in 1984, Science Olympiad is a nonprofit organization positioned as the "premier team STEM competition in the nation" (Science Olympiad, n.d.). Similar to a STEM-themed track meet, students competed in science events through regional, state, and national competitions. Not only did I enjoy science, but all of my great friends were already on my school team. It seemed a natural fit for me to join. At the time, I was unaware of how much this decision would shape my future.

I spent four years as a student participant in the Science Olympiad. These experiences involved working with my peers and coaches to build efficient balsa wood towers that we would later test against other schools. As a senior, my partner McKenzie and I designed a science-inspired Rube Goldberg-esque contraption for a rather maniacal event named Mission Possible (if you know, you know). In another event called Write It Do It, my partner Kelly and I took technical writing to a new level. The competition saw me write instructions for how to construct an object using craft supplies. My instructions were then passed to Kelly, who was given the raw materials to construct the object from scratch using only my written instructions. This event required us to be perfectly in sync yet apart; perfect communicators, but without speaking. No big deal – but we won that event at the New York state tournament twice. Overall, competitions always involved pre-dawn competition day arrivals at tournament sites. When I was successful at an event, I felt a sense of personal satisfaction that remains unrivaled in my psyche. During my college years, I returned annually to supervise an event and meet up with former competition teammates and coaches. We pick up conversations left unfinished a year prior like no time has passed at all – delighted by seeing each other reach new milestones in science and in our personal lives.

In the aforementioned anecdotes, I engaged in currencies of exchange with my peers that accumulated into what I deem to be scientific wealth. These currencies included my scientific language and communication skills, sense of teamwork and collaboration, and my science identity (a trait I had always possessed but never fully actualized until I joined Science Olympiad). Such currencies could not be captured by any traditional measure of science achievement such as standardized tests or other benchmarks. Nonetheless, I shaped and was shaped by these currencies during my time in the organization. These currencies amassed into scientific wealth, which

I define as a science learner's affluence accrued from engaging in authentic, high-impact scientific practices.

In this chapter, I ask, how can sociocultural perspectives inform our understanding of wealth and value in science, technology, engineering, and mathematics (STEM) learning? The purpose of this chapter is to explore various forms of currency under exchange within STEM education contexts in order to shed light on this question. Sociocultural theories facilitate broader understandings of these currencies – specifically by transcending traditional notions of currency as a monetary phenomenon to currency as language, skills, identity, and beyond. Through this extended metaphor, we gain a more comprehensive understanding of the wide range of impacts that high quality STEM education can have on students' scientific wealth.

The rest of this chapter proceeds as follows. I begin by exploring the nature of currency in cultivating students' scientific wealth. This discussion is useful in situating how economic currencies have traditionally undergirded national motivations for developing robust STEM education. It is in this context that I highlight important historical milestones – such as WWII and the 1960s Space Race – that signify initial STEM education development as a primarily economic endeavor. The third section explores the emergence of sociocultural theories as a response to previous STEM education research trends. I highlight how sociocultural research informs pedagogical practices that develop shared currencies within STEM education spaces. The chapter concludes by offering currencies for the future. Throughout the chapter, I introduce both personal and student narratives in order to ground this work in the lived experiences of STEM learners. I hope this chapter is as enlightening for readers as it was for me to write it.

What is Currency? What is Scientific Wealth?

Merriam-Webster (n.d.) defines currency as "something customarily and legally used as a medium of exchange" or "a measure of value". The term currency typically invokes a monetary meaning. Nations establish currencies through which individuals partake in monetary transactions. In the United States, individuals trade and exchange via the U.S. dollar. Even among paradigms where currency invokes a monetary meaning, there are a plethora of examples in which this narrow definition does not account for all exchanges. For example, roughly 48 million individuals serve as unpaid caregivers in the United States (Kasten, 2021). Transcending this traditional definition of currency, many cultural artifacts – such as art, language, and food – are also valuable forms of currency that contribute to the wealth and wellbeing of a community. For example, studies have shown that individuals who engage in artistic leisure activities experience improved life satisfaction (Bhatnagar & Imran, 2024; Hand, 2018; Lee & Heo, 2021). In STEM education, valued currencies refer both to the monetary gains afforded to individuals pursuing STEM careers and economic growth experienced by national investment in competitive STEM industries. While it is important to understand these dynamics, we can and should expand our notion of currency to recognize diverse modes of exchange between individuals engaged in STEM learning.

We can draw from Indigenous scientific scholarship in order to push our understanding of currency beyond its monetary connotation in STEM fields. Botanist and author Robin Wall Kimmerer (2013, 2024) explores how Indigenous cultures engage in scientific ways of knowing by learning the wisdom of other species. She situates this discussion within the context of the work of her graduate student – Laurie. Laurie harvests sweetgrass in order to determine whether human interaction with the plant promotes growth. Laurie found that human interactions with sweetgrass did spurn growth while neglect led to demise – a finding contrary to scientists' Western objectivist-oriented expectations. Similarly, native Canadians cultivate scientific knowledge by "building holistic pictures of the environment by considering a large number of variables qualitatively" (Berkes, 2009, p. 154). In these examples, scientists and the environment shared the currency of symbiosis. In her recent book, The Serviceberry, Kimmerer (2024) further highlights how gratitude is a primary currency of the gift economy – the marketplace of reciprocity between humans and the natural world.

Building on these traditions, we see additional currencies worthy of exploration in STEM contexts. These currencies are characterized by the skills, language, and identity that are unique to STEM learners. With respect to scientific skills, scientists utilize critical thinking, experimental reasoning, and data analysis to formulate scientific claims. A shared language develops as science practitioners work to share these claims with colleagues and the public. It is through this continual process that individuals' science identity develops – just as my high school self and peers endeavored in a process of identity-building that propelled us all to enter scientific degree programs.

Individuals cultivate scientific wealth through participation in these various modes of exchange. I define *scientific wealth* as a science learner's gains accrued from engaging in authentic, high-impact scientific practices. In the classroom, learners create scientific wealth through peer engagement, scientific practice, and enjoyment of their work. In the next two sections, I further detail how these currencies undergird STEM education, starting first from its economic origins and then its sociocultural traditions.

Economic Currencies: STEM Education Origins

In this section, we embark on a brief journey through key milestones in the growth of STEM education in order to understand the economic currencies underpinning its development. History shows us that there are always multiple perspectives in examining any event. I acknowledge that I can only tell a partial history – one that will undoubtedly omit some important details. Also, my discussion in this section concentrates on formal STEM education milestones. Individuals have been engaged in science learning since the dawn of human existence. Our evolutionary ancestors' musings with fire are likely our first encounter with STEM learning. The full history of this topic would take many book volumes, let alone one section of one chapter of one book. I choose to discuss a few historical examples that illustrate the origins of STEM education as a primarily economic endeavor.

I choose to offer the passage of the Morrill Acts (1862, 1890) as the formal beginning of STEM education in the United States. These Acts made it possible for states to establish public colleges and universities funded through the sale of federal lands (National Archives and Records Administration [NARA], 2022). These lands were almost exclusively taken from Native American tribal holdings – yet another problematic legacy for STEM education. Prominent institutions founded under these Acts include Cornell University, Ohio State University, and Texas A&M University. The focus of these institutions was to teach students (almost all white men) to become proficient in the agricultural and mechanical arts sectors – laying the foundation for modern engineering education (NARA, 2022). The second Morrill Act (1890) initiated many historically Black colleges and universities – providing valuable educational opportunities for African Americans after the Civil War. These initial developments underscore the original purpose of STEM education to be to cultivate a more economically robust agricultural industry.

The early to mid-twentieth century saw tremendous scientific advancements and accompanying growth of STEM education – driven significantly by international conflict. World War I marked a new age of global technological prowess, and unfortunately, that resulted in devastating consequences. The German forces' use of the newly devised mustard gas made soldiers the first experimental subjects of the chemical agent (Rall &

Pechura, 2000). On the US homefront, young women continually ingested carcinogenic radium-infused paint as they painted dials and other war machinery with the luminescent substance (Moore, 2017). World War II saw further escalation of these themes – most visible through the US atomic energy testing in the Marshall Islands and the eventual explosion of the atomic bomb on the residents of Hiroshima and Nagasaki in 1945 (Simon, 1997). As WWII ended, the US government engaged Operation Paperclip – a secret operation that brought 1600 German and Austrian engineers to the United States for research and development purposes (Neufeld, 2023).

In the United States, the national emphasis on STEM education skyrocketed (literally and figuratively) during the Cold War (Neal et al., 2008; Rudolph, 2002; Vossoughi et al., 2018). In 1950, the federal government established the National Science Foundation (NSF) for the purposes of promoting scientific research and STEM education (National Science Foundation Act, 1950). In a recent review, Lopez and de Mattos (2024) analyze Cold War-era government reports on science education. During this era, two themes emerged from this analysis. First, science education was a vehicle for economic progress. This goal was reflected in Executive Order 10521 – signed by President Eisenhower to expand NSF programs:

"The National Science Foundation has been established by law for the purpose, among others, of developing and encouraging the pursuit of an appropriate and effective national policy for the promotion of basic research and education in the sciences" (USA, 1954, p. 1499).

Second, science education was a mechanism for national security. The launch of Sputnik I by the Soviet Union triggered anxieties within the United States government that the Soviet science education was more effective than US STEM programs (Lopez & de Mattos, 2024). The subsequent "Space Race" saw the United States and Soviet Union engaged in a rivalry over which nation (and consequently which political system) produced the most talented scientists and engineers (Neal et al., 2008). At the head of the US space program was Wernher von Braun – a German-born aerospace engineer who was secretly moved to the United States during Operation Paperclip (Neufeld, 2019). Prior to his extraction, von Braun was an active member of the Nazi Party.

The historical milestones discussed above all position financial and national gains as the primary objective for STEM education – oftentimes at the expense of the individuals involved in the scientific processes and with flexible adherence to ethics. While the professional science practice has come a long way from the overt brutality of the early twentieth century, the economic perspectives for STEM development are still prominent today. For example, Robert May (1997) discusses measures of nations' scientific productivity in The Scientific Wealth of Nations. This includes percent of GDP spent on scientific research and development (R&D) and the quantity of scientific paper publications and accompanying citations. These metrics represent traditional benchmarks through which the impact of STEM fields is quantified today. While economic perspectives are quite informative about the global landscape of professional science – I venture that there are other ways of conceptualizing scientific wealth. In the next section, I utilize four tenets of sociocultural theories to shed light on the currencies under exchange within STEM education and how these currencies contribute to shaping learners' scientific wealth.

Sociocultural Currencies: Skills, Identity, Language

STEM learners participate in currencies of exchange that cannot be made visible through economic perspectives alone. Sociocultural theories reveal valuable modes of currency – such as language, identity, and shared experience – that are under exchange within STEM education spaces. Likewise, we can take a historical lens to understand how these theories developed in response to paradigms of time.

Emerging in the 1970s from the work of Lev Vygotsky, sociocultural theories explore the role that culture and environment play in shaping learners' cognitive development (Mercadal, 2021; Wertsch, 1991). Sociocultural theories center students' activity both with and within their environment and are less focused on learners' mental models of key phenomena (Greeno, 1998; Nasir & Hand, 2006; Saxe, 1988). Sawyer (2005) reflects this sentiment when expressing that sociocultural theories see knowledge as "not just a static mental structure inside the learner's head; instead, knowing is a process that involves the person, tools, activities, and environment" (p. 5). While this chapter examines sociocultural theories from a science learning perspective, these theories transcend academic disciplines to highlight the role of culture in learning (Gregory et al., 2004). In this section, I review four key tenets of sociocultural theories in science learning (Nasir & Hand, 2006). These tenets are:

Culture and activity constitute primary units of analysis within sociocultural research and practice.

The process of science learning renegotiates learners' personal and communal identities.

Cultural tools and artifacts mediate science learning

Science learning occurs at multiple levels

For each tenet, I describe accompanying pedagogical approaches that are valuable in fostering students' scientific wealth.

Tenet #1: A Focus on Culture and Activity

The first core tenet of sociocultural theories is a focus on students' culture and activity (Brown et al., 1989; John-Steiner & Mahn, 1996; Nasir et al., 2006; Saxe, 1998; Saxe et al., 1999; Srinivasa et al., 2022). Greeno (1996) describes activity as the "continual negotiation of people with each other and with the resources of their environments" (p. 9). Any activity is then affected by its surrounding social, historical, and cultural influences (Nasir & Hand, 2006). Additionally, students co-produce knowledge through activity (Brown et al., 1989). Thus, culture and activity are important currencies that both form and are formed by science learning.

Situated learning theory provides much of the framework for studying student activity in STEM classrooms. A sub-genre of sociocultural theory – situated learning theory relies on the study of observable patterns and discourses in social interactions to understand how students make meaning during science learning (Brown et al., 1989). Brown and colleagues (1989) also explain that students should practice authentic tasks of a field to learn the "cumulative wisdom of the community" (p. 33). Authentic tasks can broadly be thought of as ordinary practices of a culture.

In STEM fields, authentic learning involves student engagement in practices characteristic of science disciplines. For example, argumentation is one core scientific activity (NGSS, 2013; Rapanta & Macagno, 2022) that trains students in the "scientific habits of mind" (Sampson et al., 2009, p. 47). Andriessen and Sawyer (2005) describe argumentation in the science education context as "a form of collaborative discussion in which both parties are working together to resolve an issue" (p. 443). Students learn that science is distinct from other disciplines through its intentional marshaling of evidence to support and justify claims (Allchin & Zemplen, 2020). Wang (2020) employs situated learning theory to examine students' self-positioning during small group argumentation in a high school physics context. They find that students often defer decision-making to the perceived highest performing student during group work. This suggests that perceived status is another currency under negotiation amidst learning.

All STEM learning takes place within cultures – whether those of students' prior backgrounds, classroom dynamics, or broader society (Ladson-Billings, 1995a). No matter their origin, these cultures are inextricably linked to students' learning and one another. Esmonde (2017) emphasizes this point when stating that students' culture is "inseparable from cognition" (p. 6). Therefore, STEM educators can embrace culturally relevant and responsive teaching and place-based education to enact this tenet.

Culturally relevant, responsive, and sustaining pedagogies (Brown-Jeffy & Cooper, 2011; Gay, 2018, Ladson-Billings, 1992, 1995b; Paris, 2012) integrate students' cultural backgrounds into instruction and learning processes. While the pedagogies share key characteristics, the terms are distinct. As the pioneer of culturally relevant pedagogy research, Gloria Ladson-Billings (1992, 1995, 2021) writes this teaching paradigm empowers students to "maintain their cultural integrity while succeeding academically" (p. 476). The integration of students' culture into learning is done explicitly in order to promote engagement and sense of belonging in the classroom. Gay (2015) expanded on this work to highlight one core premise of culturally responsive teaching – students both cannot and should not have to separate their school and home cultures in order to succeed academically (Erickson, 1997; Gay, 2015). In the last decade, culturally sustaining pedagogy has emerged as a means of fostering students' linguistic skills and multicultural identities as a core component of democratic schooling (Alim & Paris, 2017; Paris, 2012). These developments coincide with the growth of anti-deficit scholarship as a rebuttal to early research on students' "cultures of poverty" (Burt, 1959; Jensen, 1969). Ladson-Billings (1995), Gay (2015), and Paris (2012) encourage us to implement mechanisms for students' cultural engagement and goal-directed action in the classroom. This can involve students' participation in biographical or autobiographical writing (Payne et al., 2013; Schmidt, 1999), co-authorship of classroom expectations or norms (Candela, 2005), and family engagement in educational experiences (Goodman & Hooks, 2016). In an example of these approaches in action, Candela (2005) situates their work in a primary-level science classroom in Mexico City in order to study students' role in shaping institutional norms. She finds that students develop identities as "knowledgeable and responsible participants in classroom activities" as a result of organizing their own small group norms during a science task (p. 332). Candela (2005) highlights the metaphor of identity as a currency under exchange in classrooms – an idea that I expand upon in the next section.

Place-based education (PBE) is a second approach useful in fostering students' cultural currencies. Through PBE, we can connect students' learning to the specific location in which it occurs and leverages its unique learning affordances (Habig & Gupta, 2021; Raja, 2024; Renshaw & Tooth, 2017; Vander Ark et al., 2020). PBE is also interdisciplinary and acknowledges the varied meanings that place holds for students, teachers, and community members (Demarest, 2014; Dunbar-Wallis et al., 2024). By capitalizing on the value of place in STEM learning, students exchange shared currencies of language and identity. Students also learn how the history of a place contributes to the current realities of the place and to community members' ongoing (re)constructions of the place identity. Kimmerer (2013) reflects this sentiment when stating, "to be native to a place we must learn to speak its language" (p. 48).

Existing scholarship offers insight into the myriads of ways that STEM educators can work to enact this tenet – and to detail them all is beyond the scope of this chapter. However, a few examples standout due to their wide applicability. First, Johnson and Elliott (2020) emphasize that STEM educators should work to combat the stereotype that science is only performed in laboratories by white men in lab coats. Students' cultures are sustained when they learn about the scientific successes of individuals that share their cultural background (Young et al., 2019). In addition, science teaching through real-world problem solving can situate science concepts within students' lives and communities (Aceves and Orozco, 2014; Brown, 2021). In my hometown of Syracuse, NY, Dr. Nicole Fonger (2024) and local high school students investigate the adverse health impacts of the city's lead poisoning crisis, and ultimately, use their findings to advocate for reform. Educators' use of focal events or case studies – such as lead poisoning in Syracuse (Fonger, 2024) or increased rates of diabetes among Latino communities in south Texas (Montoya, 2011) – can make science material personal for students (Gilbert, 2006). Within these examples, students accrue self-efficacy as a component of their scientific wealth as a result of participating in such learning experiences.

Tenet #2: Science Learning Renegotiates Identity

The second tenet is that students' participation in science learning renegotiates their personal and community identities. Identity is an intricate social construct. Gee (2000) offers that an individual's identity is being a "certain kind of person" that embodies traits or actions of a specific group (p. 100). Even more broadly, identity refers to how individuals see themselves within given contexts as a result of participation in certain roles and communities (Lemke, 2001; Stets & Burke, 2000). Thus, individuals can hold multiple identities that fluctuate in salience as they develop new interests, take on new roles, and evolve in their relationship with others (Carlsson, 2015: Jones & McEwen, 2000).

One core venue through which individuals develop these identities are various communities of practice. Lave and Wenger (1991) define communities of practice as “a set of relations among persons, activity, and the world” (p. 98) that evolve as experienced learners enculturate novices to the beliefs, skills, and characteristics of the community. Experienced learners act as “agents of change” when they facilitate the movement of novices from a state of “legitimate peripheral participation” to full participation (p. 37). Lave and Wenger (1991) deem this process cognitive apprenticeship. This concept draws from Vygotsky’s (1978) zone of proximal development in that it juxtaposes learners’ current level of knowledge with their future level of knowledge after assistance from critical others. Individuals’ transition to full participation involves their self-concept being aligned with the type of person who participates in a community as well as recognition from meaningful others as members of a community. Thus, students’ simultaneous internal and external recognition constitute their identity (Gee, 2000). Over time, students’ participation in communities of practice affect their goal orientations and interests in those fields (Eckert, 1990; Belenky et al., 1997). We see that identity is yet another currency under exchange via cognitive apprenticeship.

Cognitive apprenticeship and identity work have much to offer science educators and researchers. Driver and colleagues (1994) emphasize that to learn science means to enter the science community. Thus, we can design authentic learning experiences that engage students in the currencies of skill- and identity-building within shared communities of practice. One mechanism could be through exposing students to scientific role models (Ovid et al., 2023; Shin et al., 2016). Scientific role models not only show students the characteristic behaviors of scientists but also serve as “representations of the possible” (Morgenroth et al., 2015, p. 467). For students, this representation emphasizes that they are also members of the scientific community.

From a research perspective, the notion of cognitive apprenticeship directs us to explore the ways in which students receive recognition from meaningful others during their enculturation process. A primary venue for this process is through mentorship programs and research experiences. These experiences enculturate students to the scientific discipline while also heightening their science identity and self-efficacy (Atkins et al., 2020; Robnett et al., 2015). For example, Atkins and colleagues (2020) use thematic analysis to understand students' science identity development as a result of receiving mentorship. The authors find that students benefit from shared identity mentorship – meaning that their mentor shares similar characteristics (i.e gender, values) as the student. Mentors not only provide valuable reinforcement of students' science identity, but they also facilitate opportunities for students' advancement in STEM fields (Mondisa & McComb, 2015). In addition, course-based research experiences have shown promise in promoting science identity among underrepresented students in STEM, which contribute to their scientific wealth (Atkins et al., 2020; Camacho et al., 2021; Vasquez-Salgado et al., 2023). The notion of cognitive apprenticeship is so essential to sociocultural theory that it undergirds the following two tenets.

Tenet #3: Cultural Tools and Artifacts Mediate Science Learning

Sociocultural theories recognize the role of cultural tools and artifacts in shaping science learning (Brown et al., 1989; Mercadal, 2021; Robbins, 2005; Saxe, 1988; Sawyer, 2005; Wertsch, 1991). Such tools and artifacts may include the physical objects – such as lab equipment, technological systems, or specimens – that students encounter during learning. However, the notion of cultural tools can be expanded beyond the physical realm to include students' conceptual knowledge, mnemonics or acronyms, and collective memories employed throughout the learning process. Sainsbury and Walker (2011) liken scientific concepts to discourse tools that students employ during learning. Situated learning and activity theories emphasize that these tools can only be truly understood through their use, which further reinforces the importance of studying students' learning in context (Brown et al., 1989; Wertsch, 1991; Wertsch et al., 1995). Through interaction with both physical (i.e. lab equipment, computers) and mental (i.e. acronyms) tools, science learners exchange currencies of shared language and skills.

Sociocultural theories shed light on the valuable currency of language in STEM learning – a development that Lemke (2001) classifies as the "linguistic turn" in the field. In sociocultural theories, language serves as the mediator between individuals' cognitive and social functions (Luria, 1981; Pereira, 2022; Wertsch, 1998). Nasir and Hand (2006) reflect this sentiment when they write that "language serves a dual role in human functioning: it is a communication tool, and it mediates human mental action" (p. 461). Likewise, Olson (1995) dubs language learning as an acquisition of "the folkways of culture" (p. 95).

In STEM education spaces, language is a currency through which students make meaning of science concepts and develop scientific skills. Through this process, students accrue scientific wealth. More specifically, students' use of tools as currency – especially language – usher in the conceptual change necessary to promote students' learning.

Conceptual change is the process through which students modify their knowledge and beliefs as a result of new experiences (Posner et al., 1982). From a sociocultural perspective, Kelly et al. (1998) view conceptual change as "an over-time process in which novice candidates to particular social groups gain entry by adopting the language, argumentation strategies, and reasoning processes of the group" (p. 852). Thus, science learners also enter scientific communities of practice through gaining proficiency in *scientific language*. Kelly and colleagues (1998) focus on argumentation because it is simultaneously a language tool and a scientific skill – a mutual condition that makes it especially relevant for this section's discussion of language and skill currencies. In the physics classroom, these authors study students' conceptual change related to electricity. To achieve a more robust assessment of students' conceptual change (Lazarowitz & Tamir, 1994), the authors employed an argumentation-focused performance assessment with the use of physical manipulatives as tools. Jimenez-Aleixandre and colleagues (2005) also find that the most impactful argumentation tasks enact the sociocultural tenets of learning through tools and communal problem-solving. In a recent meta-analysis, Bodnar and colleagues (2016) highlight how games can serve as an important teaching tool in undergraduate engineering education. Students' interaction with tools constitutes yet another currency under exchange in STEM classrooms. Additionally, all of these authors show that sociocultural engagement with tools are crucial to promoting deep and deliberate belief change (Chinn & Brewer, 1993; Hatano & Inagaki, 2003) – a prerequisite to students' movement into communities of practice.

Tenet #4: Learning Occurs at Multiple Levels

Sociocultural theories' fourth tenet is that student learning occurs on multiple levels simultaneously. Nasir and Hand (2006) provide a concise overview of different interpretations on these levels of development – specifically highlighting the work of Vygotsky (1978) and Rogoff (1995). In Mind and Society (1978), Vygotsky distinguishes between interpersonal and intrapersonal processes. He discusses how all individual learned processes begin in response to an external activity and then are transformed into an internal activity through repeated events – a process that he deems internalization. Internalization is a primarily sociocultural process as it is both "socially rooted" and "historically developed" (Vygotsky, 1978, p. 57).

Barbara Rogoff (1995) advances this discussion by situating learner development along the personal, interpersonal, and communal planes. In her work, these planes refer to participatory appropriation, guided participation, and apprenticeship, respectively. Participatory appropriation is the process through which individuals transform their knowledge through their own participation in activities. While similar to Vygotsky's (1978) notion of internalization, Rogoff (1995) challenges the term as advancing a "static" or strictly "acquisitional" portrayal of individuals' internal construction of knowledge. Rather, participatory appropriation allows for a more fluid understanding of individuals' cognitive participation. A participatory appropriation approach can be useful to study students' science identity – specifically revealing how students respond to external recognition during the process of their identity construction. I began this chapter with an anecdote about my science identity development as a participant in Science Olympiad, which was an experience best studied through Rogoff's (2005) participatory appropriation lens.

Guided participation refers to individuals' mutual involvement in learning endeavors. At this level, Rogoff (1995) stresses the importance of studying how learners coordinate their efforts to accomplish shared goals. Much of the cooperative learning and student positioning research are driven by this interest. For example, Wieselmann and colleagues (2020) use a case study approach to investigate the small group interactions of fifth grade students during an engineering task. Not only do the authors find that boys and girls take on distinct roles within the group task, but comments from girl students are more often to go unacknowledged by the group. Campbell and Hodges (2020) use a similar method to compare the "patterns of participation" of middle school and university students studying mathematics. The authors identified five key patterns in this process: *confirming one group member* (supporting group members were satisfied with the quickest solution path posed by group leader), c*ompeting strategies* (group members competed in their problem-solving and were unwilling to negotiate a shared solution), free-for-all (group members shared solutions with disinterest towards others' contributions), *co-construction* (group members collaboratively and productively worked towards a solution), and *two member collaboration* (two group members worked collaboratively while a third observed passively). These patterns were observed among samples of middle level and university students and lend further credence to the recommendation that instructors set the classroom norms early to be of productive collaboration and problem-solving (Boaler, 2008; Wang, 2020).

Lastly, apprenticeship constitutes patterns of activity in the communal plane (Rogoff, 1995). Drawing from Lave and Wenger's (1991) idea of cognitive apprenticeship, Rogoff (1995) furthers the notion of apprenticeship beyond the study of "expert-novice dyads" to include "systems of interpersonal involvements around culturally organized activity" (p. 143). It is on the communal plane that learners exchange the currency of collective remembering – an action-oriented process in fostering collective memory (Wertsch, 2009).

Collective memory brings together the collection of individual memories in a space such that the individual feels "in the world" of an academic discipline (Hirst & Manier, 2008, p. 183). Another perspective sees collective memory as the socially constructed "realities of the past" (Irwin-Zarecka, 1994, p. 54) set "not within the minds of individuals but in the resources they share" (Irwin-Zarecka, 1994, p. 4). These definitions reveal how the established culture of the scientific fields can impact how the students of today navigate the discipline. We must acknowledge that the history of professional science and science education is deeply embedded and influenced within the culture of the time. Throughout history, we see that professional science embodied racism, sexism, ableism, and many other forms of oppression while simultaneously pushing boundaries of scientific knowledge. So, how does this collective memory impact the students of today? What does it mean for medical students to be studying medical textbooks whose past publishers capitalized on the practice of grave robbing for education (Schultz, 2005)? Or how do we reckon with some Americans' distrust of vaccine science when our nation's scientists and government officials experimented on Black bodies during the Tuskegee Syphilis Study (Brandt, 1978)? Or how do college students with disabilies engage in science classrooms knowing the history of forced sterilization as permitted by the U.S. Supreme Court in *Buck v. Bell* (1927) (Lombardo, 2022)? To ignore these questions is to ignore history. Thus, we must advance inclusive and honest history of science teachings for all STEM students in order to be true to our commitment for equity in science.

Collective memory is also a prevalent currency within the scientific history of place. Recall, Kimmerer (2013) discusses the indigenous biological knowledge that harvesting sweetgrass promotes growth of the plant – a tradition grounded in the learned knowledge of the community over time. Beyond its effect on scientific knowledge, collective remembering influences communities' attitudes towards science. For example, the 1986 Chernobyl nuclear power plant disaster has long embedded itself within the collective memory of the nations affected by the event and has impacted communities' attitudes towards nuclear power (Dudchik & Fabrikant, 2012; Hannam & Yankovska, 2017; Kalmbach, 2013). In the United States, scholars have highlighted how the racist and ableist legacy of the eugenics movement is still visible through the previously discussed "cultures of poverty" research paradigms and through commitment to a culture of high-stakes testing (Stoskopf, 2002; Jackson & Warren, 2023; Winfield, 2012).

Currencies Made Visible

This section explored how sociocultural perspectives illuminate the various currencies under exchange within STEM classrooms. Such valuable currencies include culture and identity – not only because of their effects on learners but also because they are constantly being reshaped during learning. Students' identities are (re)defined in response to social influences. For example, students' recognition as a "science person" from family and teachers contributes to their science identity, which refers to their sense of self as a scientist (Carlone & Johnson, 2007). Students' integration of this external recognition into their self-concept reflects Vygotsky's (1978) notion of internalization. Scientific skills are another form of currency. I have reviewed several important scientific skills in this chapter – such as argumentation, critical thinking, and experimentation – although there are undoubtedly many skills that I have omitted. It is through engaging with these skills that science learners become enculturated to communities of practice (Lave & Wenger, 1991). Lastly, language is perhaps the most vital currency as it mediates all other forms of action and communication during learning (Luria, 1981). For example, it would be an oversight to study students' scientific argumentation as a skill-building without acknowledging the role that language plays in cultivating this skill. Language is also the vehicle through which the currency of collective memory is shared between individuals and across generations. As Wertsch (1991) offers, we are able to free ourselves from unwanted traditions and patterns when we recognize the power of language for positive change. To do this, we can also immerse ourselves in learning the teachings of our collective memory. Collective memory, specifically, can reveal cultural norms of a discipline. In professional science, we see that the historical memory of the discipline is marred with both significant scientific advancements but also immense social injustices. We reckon with both when we exchange the currency of memory. All of the currencies summarized above help learners accrue scientific wealth and work towards science knowledge and social betterment.

This chapter introduced the concept of sociocultural currencies and scientific wealth for a few reasons. Most directly, I utilized these metaphors to challenge traditional historical motivations for development of robust and competitive STEM education. This was not done to cast aside economic perspectives entirely, nor to discount the numerous financial motivations that incentivize college students to pursue STEM degrees and careers. Rather, it was my intention that these metaphors also celebrate how students' access to high-quality STEM education can serve them in unique ways. Put another way, STEM education is a compelling venue for students' character-building, skill development, cultural growth, and other forms of learning. While all of these diverse goals may not have been front-and-center throughout history, I believe that STEM education would benefit from leaning into its sociocultural offerings. And this is not just my opinion – STEM education research bears this out. Students' science engagement increases when their science education experiences integrate their cultural backgrounds into learning (Madkins & Nasir, 2019; Stevens et al., 2016), promote real-world applications of content knowledge (Li et al., 2025; Mebert et al., 2020; Parsons & Taylor, 2011), and emphasize communal goals (Allen et al., 2015; Clark et al., 2016; Diekman & Steinberg, 2013; Nalipay et al., 2024; Vesterinen et al., 2016).

Currencies for the Future

It is my hope that this chapter has provided a fruitful overview of the diverse currencies under exchange within STEM learning spaces. By participating in the marketplace that is STEM education, learners enhance their scientific wealth – a feature characteristic among participants in scientific communities of practice. As is the case for most scientists, my work in writing this chapter has uncovered many more questions. Personally, I am intrigued by the notion of currencies of the future. That is, what are aspects of scientific wealth that remain unexplored? How can these currencies serve us moving forward?

Sterling (2010) writes that STEM education should be "fully responsive to the conditions and needs of our time" (p. 105). Our time has put the scientific enterprise at a critical juncture. In the United States, a growing number of individuals say that they distrust scientists (Tyson & Kennedy, 2024). A recent study found that only one-third of Americans are considered scientifically literate (Miller et al., 2024). Additionally, scientists are experiencing heightened anxiety around the future of grants and other research funds. To meet Sterling's (2010) challenge, we need to crystallize our intentions for science education. To do so, I ask us to consider: what are the intangible traits that can unite all science learners amidst a period of unprecedented division? I cannot begin to offer a comprehensive response for this question, but I believe that we can extend the currency metaphor and previous research into the future.

Criticality is one important currency for the future. As a core component of her Historically Response Literacy (HRL) framework, scholar Gholdy Muhammad (2020) offers a definition of criticality as “the capacity to read, write, and think in ways of understanding power, privilege, social justice, and oppression” (p. 120). Muhammad (2020) views the teaching of criticality to a learning pursuit – one that is ongoing in its “study of the state of humanity” (p. 132). Moving forward, students must develop criticality – not only better analyze the world around them but also advocate for themselves and their communities (Beck, 2005; Ginwright & James, 2002). In STEM classrooms, criticality can be cultivated by teaching through a socioscientific issues lens. As I alluded to in discussing the first sociocultural tenet, socioscientific issues (SSIs) are highly salient social challenges that explicitly connect to science (Ewing & Sadler, 2020; Sadler, 2004; Zeidler et al., 2019; Zeidler & Nichols, 2009). SSIs are grounded in sociocultural theories because they acknowledge that the nature of controversial issues varies across context (Zeidler et al., 2019). Many socioscientific issues – from hydrofracking to climate change to genetically modified organisms (GMOs) – offer educators a direct opportunity to foster students’ criticality. Additionally, Sadler (2009) calls for “the development of communities of practice in science classrooms that prioritize socioscientific discourses and development of identities reflective of engaged citizenship” (p. 12). To advance criticality as an important currency in STEM education, we should afford students the opportunity to see how science can solve pressing issues of our time, and ultimately, advance the public good.

Additionally, we should celebrate the ways that STEM students are already demonstrating criticality and social justice orietnations upon entering college. Many college students – especially those from historically excluded backgrounds in STEM – demonstrate criticality when asked why they chose to pursue a STEM degree (Herrera & Kovats Sanchez, 2022; Jaumot-Pascual et al., 2023a, 2023b; Smith et al., 2014). For example, women of color in graduate engineering programs conceptualize giving back to their community through role-modeling, mentoring others, and creating counterspaces (Jaumot-Pascual et al., 2023b). A counterspace is a space in which individuals from marginalized groups resist oppressive structures (Case & Hunter, 2012). Counterspaces maintain an oppression narrative referring to individuals’ personal relationships to the oppressive structure, and a resistance narrative focusing on how individuals demonstrate competence and strength in overcoming oppression (Case & Hunter, 2012). In STEM, counterspaces are valuable forms of resistance against a field that has historically excluded students from ethnic minority backgrounds. Students resist this exclusion by using their science education to restore justice for their communities. For Indigenous students, this may manifest through intentions to preserve tribal sovereignty such as efforts to expand broadband internet or improved health care access (Jaumot-Pascual et al., 2023a). Or, low-income students maintain a desire to bring financial stability to themselves and their family, but also acknowledge larger personal goals in the process (Madsen et al., 2023) As one student – Devon – stated:

"We [STEM students] want to get out and make money. I think that's the main goal with engineering … but obviously success is not measured through wealth. That's not something I personally believe in. I think it's just like if I can find something and enjoy doing it every day, I consider myself successful. I think it just so happens that what I'm interested in also is financially fairly stable and fairly future proof, but I think that's just a coincidence" (Madsen et al., 2023, p. 10)

Students' personal backgrounds shape their motivations to pursue STEM education and listening to these personal stories are essential to our endeavors to support students in their STEM degree path. We need to remember that students are the experts on their own lived experiences – a key component of culturally responsive and sustaining pedagogies (Gay 2015, 2018; Ladson-Billings, 2021; Paris, 2012). And it is through guided participation that we, as educators and researchers, become more adept at supporting and advocating for them. Thus, criticality is a currency through which students can not only change themselves and their communities for the better but also challenge notions of who is the "expert" and "learner" in STEM education classrooms.

Second, empathy affords us the ability to connect with fellow science learners and expand our notions of science for societal advancement. For example, Nalipay and colleagues (2024) explored students' STEM persistence intentions within a STEM service-learning context in Hong Kong. Using structural equation modelling, they find that students' sense of empathy and engaged citizenship predicts their persistence intentions in STEM. Likewise, Guney and Seker (2012) highlight how promoting students' empathy allowed students to connect science content to broader societal trends even in a high school physics lesson, which resulted in higher student interest in the content and improved nature of science beliefs. Empathy also expands our ability to both address and solve scientific problems. It is a misnomer to say that science is "value-free" or "completely objective", because our values and other passions are visible in the problems we choose to solve, and what problems we deem worthy of our time and effort. While we still rigorously apply the scientific method, we nonetheless make personal judgments throughout the scientific process. Thus, our support for individuals' empathy as students and future scientists will reinforce their initiative to solve new problems that address previously overshadowed communities and issues. This is visible in my hometown of Syracuse, NY. As I mentioned previously, we have a group of local high school students studying negative health impacts of the city's lead poisoning crisis. While not all of these students are likely to be adversely affected by not participating in this project, it is their empathy for their fellow students and identity as a Syracusan that motivates their involvement and keeps them engaged throughout. A similar project revealed the extent of water pollution in nearby Onondaga Lake, which was caused by improper waste disposal during industrial urban development. For decades, this lake was the most polluted lake in the United States (Molnar, 2024) – a title made even more unjust given its naming and close proximity to the native Onondaga Nation. A group of activists within the Onondaga Nation were instrumental to initiating lake cleanup efforts. These case studies and accompanying literature show us that cultivating students' empathy and knowledge of community can not only support learning but also advance social betterment.

The final vital currency for the future of STEM is that of joy. While hard to define, Brunsell & Fleming (2014) classify joy as "something that we know when we see it" (p. 1). Also serving as the fifth component of Muhammad's (2020) HRL framework, joy reaffirms our participation and identities as science learners. Anggoro and colleagues (2017) find that joyful science learning supports elementary-aged students' attitudes towards science. While much of the research has occurred in the elementary-level context (Cronqvist, 2021; Vartiainen & Aksela, 2013), joyful science learning need not stay relegated to this demographic of learners. We can bring the currency of joy to all levels of STEM education, because we never age out of finding joy in ourselves and our surroundings. Why would we engage in lifelong learning if we did not find joy in the process? Why would we do anything if we did not enjoy it – at least to some degree? Personally, I would not have continued with an undergraduate physics degree if I had not found joy in the communal experiences through the Science Olympiad organization in high school, nor in the college experiences of continued volunteering with that organization, nor without the support and recognition from my undergraduate peers and advisors. Amidst this current period of uncertainty in science, we can benefit from refocusing on the experiences that sparked our interest and curiosity in science in the first place. When we center these scientific experiences, the currencies under exchange during them, and the people we met in the process – we reaffirm what it means to be a science learner. Not only that, but we reestablish our dedication to advancing equitable science learning, both a as learner and teacher of science. It is through these commitments that we demonstrate our collective scientific wealth.

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Chapter 7

Scientists Are Rooted in Community: Advancing an Ecological Perspective to Support Community Engagement in STEM Education

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Chapter Highlights

The following points outline a community-centred perspective on STEM education, emphasising the role of sociocultural contexts, student identity, and theory-driven practices in supporting meaningful and sustainable participation in STEM.

- Challenging Deficit Beliefs – The practice of science is often believed to be an isolated pursuit – inaccessible and indifferent to broader community involvement. While this master narrative continues to shape perceptions of scientific work, this chapter challenges the belief that science operates independently from the community.
- Guiding Questions – I interrogate the following questions: What are the students' community roots that help them flourish in their STEM programs? In what ways do students nourish these roots through their STEM education? How can STEM education programs work to help students' thrive through community engagement?
- Community Connections as Roots The existing literature tells us that community engagement is a vital yet often overlooked component of STEM education. I use an ecological metaphor – that of roots – to support this argument. Students' communities function as critical roots that ground and sustain students' scientific interests and altruistic ambitions. This foundation of support helps students flourish both within and beyond their STEM programs.

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Introduction

Professional scientists, education researchers, and students alike hold misconceptions about the relationship between the scientific enterprise and broader communities. Among scientists, there is widespread belief that the practice of science is – and is best kept – separate from the broader public. One manifestation of this belief is the tendency of scientists to discount the benefits of citizen science ventures and underestimate the public in cultivating quality scientific data (Burgess et al., 2017; Riesch & Potter, 2014; Sullivan et al., 2014). Likewise, some of the education literature has advanced notions that students' communities – especially first-generation or immigrant communities – may lack necessary knowledge and skills to support students in STEM (Milner-Bolotin & Morrato, 2018; Suarez-Orozco & Suarez-Orozco, 2000) or promote "disorganized" environments for learning (Jensen, 1969; Lewis, 1969). Among students, survey research indicates that students perceive STEM departments to be individualistic, exclusive, and competitive (Garibay, 2018; Pawley 2019; Seymour & Hewitt, 1997). These beliefs not only collectively portray science as a field with little overlap with broader community interests but also as a difficult arena for this collaboration to take place. In short, much of the previous research traditions have focused on the challenges, rather than potential, of integrating community engagement into STEM education.

This chapter challenges these deficit-laden beliefs. Instead, I argue that community engagement is an important yet underutilized component of effective STEM education. Specifically, STEM community engagement fulfills three opportunities for growth by promoting robust science learning, improving retention, and advancing equity. First, science learning is enhanced when students address personally relevant community-based problems with scientific solutions (Chiu et al., 2023; Wiseman et al., 2020). Second, STEM retention rates also improve when students feel that scientific disciplines will serve "as a vehicle for their altruistic ambitions" (Carlone & Johnson, 2007, p. 1199). Third, several studies indicate that underrepresented minority (URM) students in STEM are more likely to exhibit communal intentions than their non-URM peers (Garcia, 2024; Garibay, 2015; McGee, 2016; McGee & Bentley, 2017), which means that we can better support these students by tending to their communal goals. This chapter supports these arguments with an extended metaphor of students' ties to communities as "roots" that undergird their success in STEM and connect them to the wider scientific ecosystem. Through an ecological perspective, we gain a more comprehensive understanding of the myriads of ways that STEM students intend to and already participate in community engagement, as well as how we can nurture their growth as both scientific scholars and community leaders.

The rest of this chapter proceeds as follows. First, I introduce and draw connections between three theoretical frameworks – Ecological Systems Theory (Bronfenbrenner, 1979), Goal Congruity Framework (Diekman et al., 2010), and Community Cultural Wealth (Yosso, 2005) – that are valuable to consider when integrating STEM education and community engagement. The second section puts these frameworks in context through discussion of STEM students' communal roots – before, during, and after their undergraduate experience. It is here that this chapter most directly challenges the notion of ideal separation between science and community. This chapter concludes with a review of curricular and pedagogical practices that sustain students' community roots and care for their future altruistic endeavors in science. Ultimately, we see that both STEM students and scientists alike are rooted in community.

Theoretical Groundings

For community engagement to flourish within STEM education, it is imperative that we first conceptualize what it means to be in community more generally. Bronfenbrenner's (1979) Ecological Systems Theory provides a robust definition that accounts for individuals' interactions with different forms of community. With this definition at the forefront, we can draw from Diekman and colleagues' (2010) Goal Congruity Framework for additional insight into how individuals navigate through various roles while in negotiation with their communities. The final theoretical framework – Community Cultural Wealth (Yosso, 2005) – provides a detailed understanding of how individuals draw support from various communities throughout their time before, during, and after their formal STEM education.

Defining Community: Ecological Systems Theory (1979)

The field of ecology explores the interactions between living organisms and their environments (Taylor, 1936). In his seminal work, The Ecology of Human Development (1979), psychologist Urie Bronfenbrenner advanced an ecological perspective to examine the interplay between individuals and their environments within the social sciences. Bronfenbrenner observed that much of the previous literature had considered the role of environment in shaping individual development, yet there was no theoretical framework that explicitly defined the components of the environment (Shelton, 2018).

At its core, Ecological Systems Theory posits that individuals experience growth both in response to their changing environments and due to their active participation in them (Bronfenbrenner, 1979). The theory is grounded in a constructivist paradigm, because individuals are viewed as active participants in their growth and development (Cobb & Yackel, 1996; Sfard, 1998; Shelton, 2018). Individuals experience constant adaptation to their environment throughout this process (Sfard, 1998). In this chapter, I adapt Bronfenbrenner's notion of environment to be synonymous with community – thus, individuals both influence their communities and are actively shaped by them.

Bronfenbrenner (1979) also characterizes the individual as in simultaneous interaction with nested systems that promote growth and development. As he likens to a series of Russian nesting dolls, such systems represent increasing levels of distance between the individual and various communities (Bronfenbrenner, 1979). Taken together, these systems constitute the ecosystem. These systems are described as follows:

- Microsystem: The microsystem is the most immediate and personal level of interaction between the individual and community. Individuals' microsystems may include relations with family, peers, mentors, and colleagues (Bronfenbrenner, 1979, 1994; Harkonen, 2001)
- Mesosystem: The mesosystem is a network of microsystems that develop as individuals enter new communities (Bronfenbrenner, 1994). Thus, the relation between an individuals' home and school communities constitutes a mesosystem.
- Exosystem: The exosystem does not involve the individual as an immediate participant yet is indirectly impactful on the individuals' growth (Bronfenbrenner, 1994). The media, government, and cultural communities can be considered dimensions of the exosystem.
- Macrosystem: The macrosystem represents the societal values and norms that are consistent across the lower-order (micro-, meso-, and exo-) systems that shape how individuals engage with various communities (Bronfenbrenner, 1979, 1994; Harkonen, 2001).
- Chronosystem: The chronosystem embodies continuities and changes of individuals and communities over time (Bronfenbrenner, 1994).

This nested systems structure defines the community in various ways. Community consists of an individual's immediate relations (i.e. with family, peers, teachers, colleagues) and broader influences (i.e. with cultural groups, institutions). Individuals experience reciprocal interactions with these communities that provide feedback on their role within the collective. Bronfenbrenner (1979) emphasizes that the notion of reciprocity marks a significant departure from previous literature on socialization processes. Specifically, he argues that previous literature has focused heavily on how the environment can affect the individual but has yet to thoroughly explore how the individual can shape their environment in turn or how the individual engages with systems beyond dyadic interactions.

Ecological Systems Theory also considers how individuals situate themselves within a community. Bronfenbrenner (1979) defines an individual's role to be "a set of activities and relations expected of a person occupying a particular position in society" (p. 85). As time progresses, the individual experiences ecological transitions as a result of changing roles or settings within the community (Bronfenbrenner, 1979). The study of individuals' growth within a broader community – and the multitude of interactions therein – is deemed development in context (Bronfenbrenner, 1979; 1994; Shelton, 2018).

This broad interpretation of community serves us well in the modern STEM education context. First, a plethora of research shows that students' STEM aspirations are shaped by many influences ranging from the microsystem (e.g. parents, teachers) to the macrosystem (e.g. cultural norms, values) (Garcia, 2024; Garriott et al., 2017; George & Kaplan, 1998; Jaumot-Pascual et al., 2023a; McGee & Bentley, 2017; Simunovic & Babarovic, 2020; Starr et al., 2022; Tey et al., 2020). For example, Garriott and colleagues (2017) used path modeling to explore the relationships between parental support, students' engineering expectations, self-efficacy, and engineering persistence among first-generation college students. They found that parental support had significant positive downstream effects on students' engineering self-efficacy and outcome expectations, which both in turn predicted students' engineering persistence. Additionally, Native American students cited the value of giving back to their community as a strong motivator to persist in STEM in the face of setbacks (Jaumot-Pascual et al., 2023a). Second, an ecological approach moves us forward from the "conquer nature" paradigm that has dominated justifications for rigorous STEM education (Beckwith & Huang, 2005; Garibay, 2015; 2018; Vaz, 2005). The National Academies of Sciences (2007) best exemplifies this paradigm in its landmark report, Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. The report called attention to the decline of scientific and economic prosperity among the American workforce compared to other countries and put forth actionable strategies for reversing this trend. It is undoubtedly valuable to consider how STEM education can further national goals, attract and retain capable future scientists, and improve our overall quality of life. However, it is likewise important for STEM education to deepen our collective understanding of the natural world by seeing the world as it is rather than only its potential for future use. Bronfenbrenner's (1979) study of reciprocity and development in context enables us to advance a symbiotic relationship between individuals and surrounding communities.

In the next section, I connect Bronfenbrenner's (1979; 1994) notion of community – specifically, the development in context approach – to Diekman and colleagues' (2010) Goal Congruity Framework. This framework shows how individuals navigate and negotiate various roles in processes that Bronfenbrenner would characterize as ecological transitions.

Navigating Community: Goal Congruity Framework (2010)

Diekman and colleagues' (2010) Goal Congruity Framework (GCF) is an important tool to analyze how individuals navigate various communities. Specifically, the framework highlights how individuals' motives and values affect their feelings of congruence within particular roles (Diekman et al., 2010; Diekman et al., 2017). Individuals are likely to seek out roles that best align with their beliefs and exit roles that conflict with their beliefs. Thus, individuals continually realign themselves within networks that allow them to actualize their goals. The authors outline this process in three phrases:

- Anticipated (in)congruity: This initial phase sees individuals anticipate feelings of congruence or incongruence prior to entering a specific role. These beliefs constitute individuals' goal affordances, which are described as beliefs about whether certain roles support or hinder particular goals. These perceptions lead to increased or decreased motivation to enter the role (Diekman et al., 2017).
- Experienced (in)congruity: In this phase, individuals' anticipated (in)congruity is juxtaposed with their actual experiences within a role (Diekman et al., 2017). Individuals receive feedback from their environment as to whether their values align with the community, and thus, whether they fit within a given role (Kristof-Brown et al., 2005).
- Seeking (in)congruity: This final phase sees individuals respond to their experiences by either maintaining congruity or seeking congruity (Diekman et al., 2017). The latter process may see individuals renegotiate their role within the environment,

organization, or community. Or, individuals may choose to leave a role entirely.

Individuals seek congruence through continual feedback between themselves and their environment. The broad definition of environmental influences – as afforded by Ecological Systems Theory – enables us better understand these modes of feedback.

The Goal Congruity Framework has been successfully utilized to study students' STEM ambitions. A plethora of studies have found that both high school and college students alike perceive STEM fields to afford fewer communal goals than individual goals (Boucher et al., 2017; Cheryan et al., 2015; Clark et al., 2016; Diekman et al., 2010; Diekman et al., 2017; Diekman & Steinberg, 2013; Henderson et al., 2022; Hoh, 2009). However, many students – especially URM students – seek out a STEM degree for altruistic purposes, such as a desire to help their family or serve others (Carlone & Johnson, 2007; Garcia, 2024; Jaumot-Pascual et al., 2023a, 2023b; McGee, 2016; McGee & Bentley, 2017). Thus, these students likely anticipate incongruity between their altruistic ambitions and a STEM education, which in turn reduces their motivation to pursue a STEM degree (Diekman & Steinberg, 2013). Conversely, Steinberg and Diekman (2017) found that students' belief in the communal affordances of STEM degrees predicts their positive feelings towards STEM career paths. Thus, students are more likely to pursue a STEM degree if they perceive overlap between their personal and STEM communities.

Goal Congruity Theory holds additional explanatory power for students' experienced (in)congruity within STEM programs. First, students with direct experience of communal activities – such as mentorship or volunteering – maintain greater belief about communal affordances of STEM programs (Belanger et al., 2020; Montoya et al., 2020; Steinberg & Diekman, 2017). Student mentors likewise experience benefits to their STEM persistence – a testament to Bronfenbrenner's (1979) study of reciprocal interactions. Second, students' exposure to altruistic role models in science has led to heightened science interest (Cheryan et al., 2015; Clark et al., 2016; Gladstone et al., 2024; Gladstone & Cimpian, 2021; Shahali et al., 2017). Third, students' perceived communal affordances in STEM moderates their sense of belonging and persistence within their chosen program (Belanger et al., 2020; Isenegger et al., 2023; Yu et al., 2025). For example, Carter et al. (2021) found that highlighting the altruistic outcomes of a geoscience career are more attractive for students than other reasons for pursuing the degree (e.g. working outdoors). These findings indicate that STEM degree programs that demonstrate commitment to communal goals are positively received by students, which in turn facilitates higher student retention.

Ecological Systems Theory and the Goal Congruity Framework work in tandem to explore how students both conceptualize community and navigate through community before and during college. Both theories recognize that students have agency to choose to enter and exit various roles in what Bronfenbrenner deems ecological transitions. (Bronfenbrenner, 1979, 1994; Diekman et al., 2010). Importantly, these decisions are driven by continual feedback from both students' micro- and macrosystems (Diekman et al., 2017). Building on Bronfenbrenner's (1979) broad definition of community, the Goal Congruity Framework sheds light on the fact that students' non-communal perceptions of STEM will have disproportionate adverse effects on URM students' retention. This occurs because these students are more likely to maintain communal goals than their non-URM peers (Diekman et al. 2011; Diekman et al., 2017). But how do persistent URM students leverage community support that surmounts these perceived barriers? The third theoretical framework – Community Cultural Wealth (Yosso, 2005) – is valuable for illuminating the many ways that community supports students' success.

Leveraging Community: Community Cultural Wealth (2005)

Yosso's (2005) Community Cultural Wealth (CCW) Framework emerged as a challenge to previous theories of cultural capital. In previous decades, education theories of cultural capital espoused a belief that communities contribute valued capital to society, yet some communities are culturally wealthy while others are culturally poor (see Valencia & Solorzano, 1997; see Valenzuela, 1999). Bourdieu and Passeron (1977) argued that students from culturally poor communities (i.e. Communities of Color) could access greater resources through social mobility. Thus, formal education is a vehicle through which these students can gain entrance into wealthier community echelons. Yosso (2005) drew attention to two core flaws of this perspective. First, the assumption follows that Communities of Color lack certain skills and resources needed to advance socially. Second, the values and outcomes of White communities become the standards upon which all other communities are judged. The CCW Framework addresses these flaws by centering how Communities of Color nurture students' various forms of cultural wealth. Drawing from Solorzano's (1997) tenets of critical race theory in education, the Framework decenters deficit-laden perspectives and instead highlights the strengths that students bring to educational spaces. The CCW Framework highlights six forms of capital as follows:

- Aspirational capital: This form of capital centers how Communities of Color nurture a culture of possibility in the face of obstacles. Yosso (2005) highlights previous scholarship showing how Chicano parents maintain high mobility aspirations for their children despite low educational attainment compared to other demographics (Solorzano, 1992). Similarly, Shelton and Thompson (2023) celebrate how undocumented Latinx students maintain a desire to serve others amidst ongoing immigration uncertainties and political hostilities. Even when URM students did not have clearly defined educational goals, they desired to be successful college students (Perez II, 2017). Within STEM education, aspirational capital was visible in 28 out of the 33 studies included in Denton and colleagues' (2020) recent review. For example, Dika and colleagues (2018) found that aspirational capital was a key motivator for URM students persisting in engineering.
- Linguistic capital: Linguistic capital refers to students' skills attained through communication in multiple languages (Yosso, 2005). Multilingual students often develop cross-cultural awareness and literacy when serving as communication liaisons between school and familial communities (Faulstich Orellana, 2003). STEM students and support staff often viewed bilingualism as helpful for their respective career development (Chavez, 2024; Heyman, 2016; Pacheco & Chavez-Moreno, 2021; Zamudio, 2015).
- Familial capital: Familial capital refers to students' cultural knowledge nurtured by family and community memories (Yosso, 2005). This form of capital parallels the notions of funds of knowledge among Mexican American communities (Moll et al., 2006) and pedagogies of the home among Chicano communities (Delgado Bernal, 2001; Garcia & Delgado Bernal, 2021). The STEM education literature contains numerous examples linking students' STEM aspirations to their familial backgrounds. Students cite robust family involvement in their learning (Longoria, 2013) – oftentimes sparking their interest in STEM from an early age (Dou et al., 2019; Pattison et al., 2022; Salvatierra & Cabello, 2022; Tolbert, 2017).
- Social capital: This form of capital centers how students draw from community networks to facilitate their success (Denton et al., 2020; Yosso, 2005). While in STEM degree programs, students' social capital is often facilitated by peers (Revelo Alonso, 2015). Students' strong

relationships with faculty mentors can also strengthen their social capital (Dika, 2012; Mondisa, 2020; Salazar et al., 2019).

- Navigational capital: Stanton-Salazar & Spina (2000) define navigational capital to be the "set of inner resources, social competencies, and cultural strategies that permit individuals to not only survive or even thrive after stressful events but also to draw from the experience to enhance subsequent functioning" (p. 229). Denton and colleagues (2020) found that most scholarship studying navigational capital focused on individuals used resources to maneuver through higher education (see McKnight, 2016; see Mobley & Brawner, 2012). For example, Sausner and colleagues (2024) drew attention to how Black and Latino students navigated through STEM in a variety of ways. Many of these students went out of their way to seize opportunities, even if they did not completely align with their interests, but rather because these opportunities represented a chance for success. While the authors found that female students were likely to acknowledge and utilize external support throughout the program, Black male students tended to absorb a personal responsibility of success.
- Resistant capital: This sixth form of capital sees students engaged in oppositional behavior that challenges racism, sexism, ableism, and the status quo (Yosso, 2005). From an early age, children learn about acts of resistance from their parents (Delgado Bernal, 1997; Robinson & Ward, 1991; Villenas & Moreno, 2001). Within STEM education, Revelo and Baber (2018) found that Latino engineering students embodied resistance through role modeling and community outreach. These students also saw their STEM success as their means of resisting deficit narratives about their communities.

Yosso's (2005) CCW Framework sheds light on how persistent students in STEM utilize community resources as they navigate through STEM education. In the next section, I draw upon previous literature to demonstrate how these resources motivate students' community aspirations within STEM (Burt & Johnson, 2018; Denton et al., 2020; Habig et al., 2021; Rincon et al., 2020; Rincon & Rodriguez, 2021; Samuelson & Litzler, 2016).

STEM Students' Community Roots

In a recent piece, Jaumot-Pascual and colleagues (2023a) shed light on the experiences of undergraduate Native American students in the computer science field. Using visual storytelling methods common to Native American groups, students shared their communal motivations for pursuing computer science. Their stories centered around two themes: a desire to give back and a desire to engage with Native communities. For example, one student – Libby – identified role modeling as one venue for both giving back and engagement, stating "If I'm in computer science as a Native woman, there's no reason why I can't take this part of me and try and encourage other people with their own computer science journey" (Jaumot-Pascual et al., 2023a, p. 988). Along similar themes, high achieving Black and Latino students not only cite a desire to give back but are also likely to use their STEM education to act critically and advance justice towards their communities (McGee, 2016; McGee & Bentley, 2017). I see such themes emerging even within my own work within our college admissions team. In this role, I have interviewed a diverse group of high school students interested in pursuing STEM degrees. Countless students center themes of community in our conversations – whether it be around receiving support from family and teachers during school, or engaging with community during co-curricular activities, or valuing careers that enable them to give back to others. I recall one student who spoke about how her part-time job at a senior living facility, and how her engagement with residents therein sparked an interest in studying public health. Ultimately, her goal was to conduct research into dementia-related diseases. Another student described her experience being raised on her family farm in rural upstate New York. She intended to study biology in college, which she felt would allow her to showcase her passion for sustainable agriculture and work in the environmental policy field in the future. These students exemplify a growing population of STEM students, because an increasing number of students cite a desire to "make a difference" as motivation for pursuing a STEM career (Lakin et al., 2021; Mwangi et al., 2021; Vesterinen et al., 2016).

This trend challenges the prevailing views about STEM fields, which is that these disciplines are isolated and individualistic in nature (Boucher et al., 2017; Diekman et al., 2010; Garibay, 2015; Hazari et al., 2010; Nicholls et al., 2007; Parsons, 1997). Diekman and colleagues (2010) found that college students believe that STEM fields are more likely to serve individual rather than communal goals. Students' image of a scientist is denoted with these individualistic (and often masculine) undertones, even while acknowledging the various roles that a scientist fulfills in different contexts. Parsons (1997) underscored these findings:

> Even in the midst of fulfilling his various roles as worker, friend, spouse, and parent, the scientist is characterized as a person who prefers to be left to himself, to be left alone with his mind and his books. (p. 758)

This stereotype endures over two decades later, as evidenced by Pawley's (2019) finding that students conceptualize the ideal engineering student to be a young White male without major external obligations. If these perceptions persist, we risk communal-oriented students – who are also more likely to be from a historically marginalized background – leaving the STEM pipeline altogether. This assertion is supported by both observational and experimental research. For instance, Vida and Eccles (2003) found that valuing collaborative work is negatively associated with both choosing a science career and being employed with a science field. Likewise, students' perceptions that STEM does not afford communal opportunities are repeatedly associated with declines in motivation, interest, and positivity towards STEM careers (Brown et al., 2015; Brown et al., 2018; Thoman et al., 2015). Conversely, students that are shown or participate in community engagement opportunities in STEM do report higher levels of motivation, interest, and positivity (Brown et al., 2018; Thoman et al., 2015; Weisgram & Bigler, 2006)

In response to these findings, Brown and colleagues (2018) deemed community perspectives a "new vantage point" from which educators and researchers alike can promote students' engagement with the STEM pipeline (p. 21). Thus, we must understand the various ways that students leverage and promote community within STEM throughout their educational journeys. The rest of this section details these trends before, during, and after students' college years.

Interest Takes Root: Pre-College STEM Experiences

Students' STEM interests "take root" in their early community experiences. Research shows that many students' STEM interest and community engagement aspirations grew in tandem during their childhood years. Students' childhood years represent a critical period for identity development (Branje et al., 2021; Kroger, 2006). Identity is a complex social construct that involves both internal reflections (i.e. who am I and who do I want to be?) and external considerations (i.e. how do others perceive who I am?) (Gee, 2000; Jones, 2009; Krogh & Andersen, 2013). Importantly, an individual's identity is context-dependent – meaning that their identity is not only shaped, in part, by external recognition but also evolves in response to new interests, roles, and relationships (Carlsson, 2015; Carlsson et al., 2015; Jones & McEwen, 2000). Thus, students' identities shape and are shaped by how they engage in community. These characteristics bode well for examining identity – and by extension, community involvement– via the Ecological

Systems Theory and Goal Congruity Framework.

Identity is an important construct within STEM education, because it shapes students' perceptions of their possible future "selves" (Markus & Nurius, 1986). We aspire for students to see themselves as a "science person" – someone who enjoys and can succeed in science – and thus we must understand how this science identity is cultivated both before and during students' college experiences. This is also important because science identity is a strong predictor of science interest and science career aspirations among students of all ages (Roth & Tobin, 2007; Royse et al., 2020; Starr et al., 2020; Stets et al., 2017)

The Microsystem: Parents and Families

Students' families remain the most immediate community that influences their academic dispositions (Burt & Johnson, 2018; Deng et al., 2023; Dotterer et al., 2009; George & Kaplan, 1998; Madsen et al., 2023; Mak & Chan, 1995; Peralta et al., 2013; Russell & Atwater, 2005; Strayhorn, 2010). Students' families are active participants in their students' education and provide resources and support for their success (Ritter & Mont-Reynaud, 1993), which challenges the deficit views towards ethnic minority families' educational involvement (or perceived lack thereof) in their children's education. Historically, these parents have been falsely stereotyped as uncooperative or apathetic towards their children's education (Comer, 1988; Erikson, 1968), or discredited as aggressive or unreasonably ambitious for their children (Comer, 1988; Lawrence-Lightfoot, 1978). While these sentiments persist in the literature, there is no research or theoretical basis to support these beliefs.

Regarding students' STEM interests, families represent the first microsystem in which students' science interests "take root", which also means that family influences affect the students' future growth within STEM. For example, George and Kaplan (1998) found that parents encourage students to develop pro-science attitudes through engagement with out-of-school science activities and involvement in students' schooling. Burt and Johnson (2018) drew on the interviews with 30 Black men in graduate engineering programs to identify how early influences cultivated their interest in STEM. The authors found that parents employed resistant and navigational capital to promote students' success, specifically by working to enroll their children in advanced courses within school and advancing the shared value of education as an "equalizer" at home. Likewise, Russell and Atwater (2005) highlighted how the parents of African American students in STEM set high expectations for their students' success – a theme that exemplifies aspirational capital. Aspirational capital among students' family communities is a theme across qualitative studies of STEM students' early science experiences (Samuelson & Litzler, 2016). On a broader scale, the Third International Mathematics and Science Study (TIMSS) found that 8th grade students' perceptions of the utility of science were significantly influenced by their parents' views towards science (Beaton et al., 1998). In all of these studies, parents and immediate family instill within their children pro-science attitudes and curiosity about the world.

The Mesosystem: Teachers, Counselors, and Co-Curricular Activities

Following Bronfenbrenner's (1979) framework, we can consider the mesosystem comprising students' home and school communities in partnership. In this vein, Burt and Johnson (2018) reflect this communal sentiment when they state, "cultivating and nurturing kids' early STEM interests is not a parent vs. teacher binary, but rather a community affair" (p. 265). Teachers are important catalysts for students' interests in STEM (Haney et al., 2002). Teachers that affirm students' potential, rather than limitations, for pursuing STEM subjects foster students' genuine interest in those fields (Brown & Kelly, 2007; Burt & Johnson, 2018; McGee & Pearman, 2014). In one study, teacher enthusiasm for STEM was found to have a positive indirect effect – acting through students' intrinsic motivation – on students' GPA (Jungert et al., 2020). This result shows that teachers can excite students' internal aspirations for success, which then have downstream effects on tangible school outcomes. Additionally, teachers that integrate students' community and cultural history into their curricula strengthen students' aspirational capital (Burt & Johnson, 2018). Other school personnel – such as guidance counselors – can also affect community and students' STEM orientations. The American School of Counselor Association's (ASCA) ethical standards (2022) state that counselors should "promote equity and inclusion through culturally affirming and sustaining practices honoring the diversities of families" (p. 6). Thus, high school counselors should be adept at forging relationships between students' home and school communities. Guidance counselors also provide key information about and advise on postsecondary opportunities and thus influence students' future aspirations.

Outside of school, early STEM immersion programs are additional spaces in which students can become initially integrated into the scientific community. A plethora of research supports this assertion and likewise shows that these experiences are crucial to igniting students' interest in science (Betz et al., 2021; Kong et al., 2014; Lehmeidi Dong et al., 2023;

Vesterninen et al., 2016; Young et al., 2017). Such early immersion programs can include summer camps (Prasad et al., 2022; Sowells et al., 2016; Yilmaz et al., 2009), museum visits (Adams et al., 2014; Lavie Alon & Tal, 2015), after-school programs (Chittum et al., 2017; Dabney et al., 2012; Kennedy et al., 2016; Young et al., 2017), or job shadows (Moriarty et al., 2013). Simultaneously, these programs support students' development as engaged citizens. Vesterninen et al. (2016) conducted 35 interviews with 15-19 year old students at a science camp to learn about how they engage in altruism and their views about the role of science in that work. The authors found that students participate in a wide array of activities focused on making the world a better place – these ranged from personally responsible activities (e.g. helping a friend in need, donating to charity) to participatory activities (e.g. mentoring younger students, leading recycling initiatives at school) to career preparatory activities (e.g. studying for a career to help others). These findings demonstrate that students not only desire to engage in community, but they are already involved in doing so before they enter college.

\While students' family and school experiences can positively shape students' STEM aspirations, it is also important to acknowledge the ways in which these influences can adversely affect students. Literature indicates that girls face socialization – both from the microsystem and macrosystem – away from STEM careers due to stereotypes that science (especially natural or hard science) is a masculine pursuit (Archer et al., 2013; Master et al., 2016; Parsons, 1997; Schreiner & Sjoberg, 2007). This conclusion is derived, in part, from the finding that girls demonstrate less overall interest in science despite equal performance in the subject compared to boys (Haworth et al., 2008). Even students as young as age 6 have shown associations of science with masculinity (Hughes, 2001). From a Goal Congruity perspective, these young girls have already manifested incongruence between their gender identity and the pursuit of STEM. For older students, a backlash effect may result from their negative prior experiences with school. Moore III and colleagues (2003) identified the presence of a "prove-them-wrong syndrome" among African American men in engineering, which manifested as a form of resistant capital against detractors during their k-12 years. These motivations continued into students' college years where their Blackness was often under assault in their STEM departments (McGee & Martin, 2011). Similarly, researchers have identified the ways in which Latino students are underserved by their counselors. Students often cited biased treatment and low academic expectations in these experiences (Cavazos Vela et al., 2023; Malott, 2010). Despite such experiences, these students strive to actualize their STEM career and community engagement aspirations.

The Exosystem: Cultural Community Networks

Bronfenbrenner (1979) describes the exosystem to contain individuals' surrounding environments that they may or may not directly interact with yet are nonetheless influenced by. Such influences include the government, media, and extended family. For this chapter, I will highlight the role of students' extended family, or broader cultural networks, in shaping students' STEM community engagement intentions.

Students' extended cultural communities have a profound positive impact on their desire to serve the community through their STEM degree and career, especially for underrepresented minority students in STEM (Espinosa, 2011; Garcia, 2024; Garriott et al., 2017; Herrera & Kovats Sanchez, 2022; Howard et al., 2024; Jaumot-Pascual et al., 2023a, 2023b; Kanagala et al., 2016; Kimmerer, 2013; Madsen et al., 2023; Page-Reeves et al., 2019; Rendon et al., 2020; Smith et al., 2014). Specifically, these students' learned values of reciprocity, community, and collectivism are key motivators for their entrance into and persistence in college STEM programs.

One of the most common themes emerging from the literature is that of students' desire to give back to their community through science. Jaumot-Pascual and colleagues (2023a) define giving back as "engagement in activities that contribute to the empowerment of one's communities and creating positive change" (p. 882). In their work with indigenous students, the authors expanded this definition to include culturally-connected giving back, which refers to "activities where Native individuals contribute to the empowerment of Native communities and to create positive change through the engagement of Native values, cultures, and resources" (p. 883). Biologist and Indigenous scholar Robin Wall Kimmerer and her collection of works (2013; 2024) speak to these cycles of reciprocity between humankind and nature. Black and Latino students also demonstrate aspirations to serve their cultural communities and remain connected to them during college, which can manifest by their choice to attend Historically Black Colleges & Universities (HBCUs) or Hispanic-Serving Institutions (HSIs). Latino students also hold familismo – a cultural value centering on family loyalty, dedication, and closeness – in high regard (Calzada et al., 2013; Estrada et al., 2016; Hurtado et al., 2010; Marin & Marin, 1991; Martinez, 2013; Perez II, 2017). In STEM fields, familismo can not only serve as a form of familial, navigational, and social capital.

A second emergent theme is that of the importance of students' pre-college STEM role models, which serve as a mechanism for generating students' positive "figured world of STEM" and thus promoting perceived congruence between their identity and STEM fields. Tan and colleagues (2013) noted that all middle school aged girls interviewed in their study demonstrated familial capital in their science pursuits. One student cited discussions with two close family members who are doctors as important for their science interest. Likewise, students' positive recognition from meaningful others towards their identity as scientists supported their beliefs that "people like them" have opportunities in STEM. This theme continues into students' college years, because altruistically-engaged STEM role models resonate with students and promote their sense of belonging (Fuesting & Diekman, 2017; Gladstone et al., 2024; Gladstone & Cimpian, 2021; Marx & Ko, 2012)

Consequently, students' perceived incongruence between their cultural norms and STEM programs can be a source of conflict (Herrera & Kovats Sanchez, 2022; Page-Reeves et al., 2019; Smith et al., 2014; Tibbetts et al., 2016). Guiffrida and colleagues (2012) write that students of color face additional difficulties ingratiating into predominantly white institutions due to differences between their cultural norm of collectivism (Hofstede & Rowley, 2002; McClellan et al., 2005) and the institutional norm of individualism (Triandis et al., 1998). Even before college, some students may self-select out of the STEM pipeline to avoid these potential value conflicts.

In summary, students' pre-college communal experiences not only shape their STEM interests but also orient themselves towards future community engagement through science. Throughout a wide range of social science literature, we see emergent themes that speak to the benefits of community integration within students' early educational experiences. For example, Rogers et al. (2018) argued that a "collaborative community-focused perspective" (p. 38) is most advantageous for supporting students' needs. Additionally, we see evidence that younger students already have their sights set on community engagement prior to entering college (Vesterninen et al., 2016), and many underrepresented minority students in STEM are driven by community-centered cultural values to pursue careers in STEM (Garcia, 2024; Jaumot-Pascual et al., 2023a; Page-Reeves et al., 2019).

Nourishing Roots: College STEM Experiences

Mentor relationships, peer networks, and high-impact experiences are all forms of STEM students' community engagement during college. These activities serve to nourish the roots with students' communities upon entering college. This section likewise examines how students engage with micro- and macro-level communities during their college years.

The Microsystem: Mentors, Peers, and High Impact Activities

Faculty and academic mentors are instrumental to STEM students' sense of belonging, self-efficacy, and science identity during college (Baker & Griffin, 2010; Ceyhan & Tillotson, 2020a; Erkut & Mokros, 1984), particularly for first-year students (Fuentes et al., 2014). Supportive mentorship requires that faculty and students make a commitment to continually engage and cultivate an ethic of care (Johnson & Griffin, 2025). For Latino STEM students, a hypercompetitive environment created few instances to cultivate familismo within academic spaces, but interactions that were successful centered on values of trust, reciprocity, and care (Carlone & Johnson, 2007; Lopez et al., 2019). Additionally, mentorship and the creation of counterspaces are areas where Native students enact values of culturally-connected giving back (Jaumot-Pascual et al., 2023a). Native students in STEM see themselves as having a unique capacity to inspire others during their program (Page-Reeves et al., 2019). Native students in the computer science field look to align their scientific endeavors with tribal advancement – citing the role that their computer science knowledge is useful in supporting environmental protection, mental health, and technological sovereignty initiatives on tribal lands (Jaumot-Pascual et al., 2023a). Such opportunities to serve the community were strong motivators to persist in STEM in the face of setbacks. In a similar vein, giving back served as "one of the most fulfilling things" that Native women did during their college years (Powers, 2018, p. iv). These findings echo previous sentiment demonstrating that Indigenous' students persistence in college increases when their education focuses on giving back to the community (Brayboy et al., 2012).

Peer networks also serve as centers of community for college students (Arevalo et al., 2016; Perez II et al., 2018; Watkins & Mensah, 2019). In one peer mentoring program at Arizona State University, peer mentors served dual roles for students as academic guides (i.e. sharing key information) and psychological supports (i.e. a caring friend), which demonstrates peers' roles as sources of navigational and social capital (Yosso, 2005; Zaniewski & Reinholz, 2016). From the academic angle, Salomone and Kling (2017) explored the effects of peer-led learning sessions across five introductory STEM courses. Students who attended these sessions not only had higher course grades than previous students, but also maintained higher retention rates in their programs two years later. It is crucial to support STEM students' social networks as they are important retention mechanisms (Ceyhan et al., 2019; Damkaci et al., 2017; Gatz et al., 2018; Salomone & Kling, 2017; Turetsky et al., 2020; Zwolak et al., 2017), because they act as "sticky webs" that ingratiate and encourage students to persist through challenging academic environments (Moynihan & Pandey, 2008). When students position themselves centrally within the figurative "web", they are much more likely to persist in STEM. For example, Zwolak and colleagues (2017) used network analysis to study students' positioning within an introductory physics class. The authors found that students at the center of the classroom peer network had a higher rate of persistence in later physics courses. For women and girls in STEM, supportive peers foster feelings of belonging that help them counteract the effects of exposure to sexist messages (Leaper, 2015). Similarly, Revelo Alonso (2015) and Revelo and Baber (2018) found that engineering students cultivated resistant and social capital through peer-led professional organizations.

I have just discussed who STEM students engage in community with during their college experiences. But, where and how does this engagement take place? It is here that we can turn to high-impact STEM practices (Ives et al., 2024; Kuh, 2008; Pendakur et al., 2020; Peters et al., 2019). These practices refer to activities that have been repeatedly shown to increase student learning, retention, and engagement within STEM programs and institutions overall (Kilgo et al., 2015). These practices include undergraduate research experiences, studying abroad, first-year seminar courses, service learning, and living learning communities. While all are valuable, undergraduate research and service learning are the most directly applicable to discussions of STEM students' community engagement. First, students' participation in undergraduate research and service learning both facilitate their entry into scientific communities of practice (Lave & Wenger, 1991). It is in these environments that students learn key skills – such as critical thinking, experimental design, and data analysis – needed to be successful in science (Ceyhan & Tillotson, 2020b; Seifan et al., 2022). And second, these environments socialize students into a collaborative environment, which reinforces the notion that science is a community endeavor (Saavedra et al., 2022; Vesterinen et al., 2016). Nalipay and colleagues (2024) expanded this line of research by finding that students' sense of empathy cultivated during a service learning course also had downstream effects on their citizenship attitudes and STEM persistence intentions. This interesting finding demonstrates that cultivating students' knowledge of community can support learning and also promote social betterment.

In all of these forms of engagement, students seek congruence between their STEM activities and community service ambitions (Garcia, 2024; Herrera & Kovats Sanchez, 2022; Nalipay et al., 2024; Reyes et al., 2024; Saavedra et al., 2022; Thoman et al., 2015; Vasquez-Salgado et al., 2015). This is especially true for students of color. In their seminal work, The Equity Ethic, McGee and Bentley (2017) explore how high-achieving Black and Latino students' STEM aspirations are grounded in a concern for helping others. In a series of interviews with medical students, Antony (1996) identified that one of the key motivating factors for students pursuing medical school was a desire to serve the public. For Latino premedical students, "giving back" to address health disparities was a cultural asset that led to degree completion in four distinct ways – employing Spanish language skills within medicine, volunteering during college within communities, creating infrastructure for future premedical students at the institution, and desiring to practice medicine within underserved communities in the future (Garcia, 2024). Similarly, ethnic minority research assistants in STEM who see the altruistic value in their research feel more psychologically connected to their work and, in turn, more engaged with it (Thoman et al., 2015). Lastly, Yu and colleagues (2025) found that sense of belonging mediates the relationship between STEM students' feelings of goal congruity and persistence.

Challenging the Institutional Macrosystem

Despite these positive motivating influences described above, it is important to acknowledge reasons why students may not be able to fully participate in these community-building initiatives, and how institutional macrosystems might hinder their participation. During college, URM students face conflicts between their social justice intentions and the future demands of a competitive STEM career (Herrera & Kovats Sanchez, 2022; Tran, 2011; Tran et al., 2011). All interviewed participants in Herrera and Kovat Sanchez's (2022) study noted a lack of social-justice oriented role models in their STEM programs. Underrepresented students of color in STEM even report compartmentalizing their social and academic identities from their science identities (McCoy et al., 2015).

Administrative efforts to improve retention for students from underrepresented groups can also differ drastically from students' desires and needs (Guillory & Wolverton, 2008; Luedke, 2017; Page-Reeves et al., 2019; Smith et al., 2014). Guillory & Wolverton (2008) highlighted these differences in regard to Native college students. They found that administrators focused retention efforts on greater financial aid for students. While financial support is undoubtedly important in helping students persist, students also spoke about a further desire to have their college connect with tribal communities. Latino students may experience conflict between institutional norms and familismo. As Frederick and colleagues (2023) explained, the collectivist core of familismo is incongruent with dominant higher education paradigms that reward individualistic pursuits and assume that students prefer separation from family during college. Ultimately, these examples reflect what Vasquez-Salgado and colleagues (2015) deem "home-school value conflicts" or "home-school cultural value mismatch". These norms can also manifest through outright racism, which forces students to exhibit resistant capital. For example, one student in McGee and Bentley's (2017) study – Eduardo – was advised to "stop hanging out with friends from his hometown" and "to tone down his accent" (p. 1646). Institutions and STEM departments cement structural racism when their programs work to "fix" or "assimilate" underrepresented students of color into dominant (i.e. White male) paradigms while ignoring their role in perpetuating racism therein (Johnson et al., 2011; McGee, 2020).

A third hindrance is that students may not be able to afford to take unpaid internships or research experiences during their college experience – roles that produce the "invisible labor" of institutions (Hart, 2014; Steffen, 2010). To compound this challenge, undergraduate students are increasingly older, raising families, and are more likely to be low-income (Cote, 2023; Purdy, 2021). Many institutions have recognized the socioeconomic barrier that students face to these activities and have attempted to alleviate the burden by providing stipends to participating students, but this is not the norm (Guessous et al., 2015; Schmidt et al., 2003). Additionally, the structure of advanced scientific training (e.g. REU programs) can push students out of the STEM pipeline if they are unable to commit to a potential out-of-state program lasting several months. Given that low-income and first-generation college students are more likely to attend college closer to home, these programs may not be attainable or desirable for these students. Furthermore, an increasing number of students are electing to live at home for college (UCAS, 2000) – a trend that some scholars say hinders academic socialization (Garza & Fullerton, 2018), but I would argue rather reflects students' community cultural wealth that support their success (Patiniotis & Holdsworth, 2005; Yosso, 2005). But, while these students may not be engaged in traditional high-impact activities, STEM programs should recognize the valuable skills that these students are mastering within their various roles. For example, students likewise learn discipline and time management skills – just like they would in a research laboratory setting – from holding down a paid off-campus job or raising a family while simultaneously attending college classes. Therefore, we should expand our collective notion of what constitutes a high-impact experience so that we can recognize how diverse students are championing STEM success and community engagement beyond what the literature suggests.

Putting Down Roots: Post-College STEM Experiences

Not only do STEM students maintain aspirational capital towards community engagement prior to and during college, but they also contribute to their scientific and social communities in many ways after their undergraduate STEM education concludes. The literature shows that early career scientists enter their professions with a desire to serve others and cultivate community within such spaces (Carrigan 2017; Gibbs Jr. & Griffin, 2017; Litchfield & Javernick-Will, 2015; Villarejo et al, 2008). A survey of recent URM STEM graduates identified attributes that would make research careers more attractive (Villarejo et al., 2008). The attribute, "knowing that scientific knowledge they created would help members of the community", was the second-most positively rated attribute of those provided. Additionally, surveyed alumni that left research frequently cited their desire to serve others in a more direct way in their career. Gibbs Jr. and Griffin (2017) more recently interviewed 38 early career science PhDs and found that many who pursued the academic faculty career path shared a passion for engaging with others. Many participants cited a goal to create community within their academic department, even if their college experiences lacked such connections. For example, one participant – Alicia – pursued an academic career for communal ends, stating, "It's rewarding to think about being able to mentor students. That's really what I'm passionate about." (p. 718). These sentiments contrast sharply with her own engineering experiences in which a male colleague advocated against hiring a female student due to his belief that "women can't do math and they're not really competent in mathematics." (p. 717). Alicia's persistence in STEM exemplifies her resistant capital.

STEM students' familial capital is another hallmark of their post-college experiences. McAlpine and colleagues' (2014) longitudinal study of graduate scholars and early career professionals revealed the extent to which students' families remain core to their professional journeys. These individuals were at various stages of their lives, but all of whom were "putting down roots" in their respective communities. Scientists must navigate the balance between their professional and personal lives, which many cited as a challenge during their doctoral studies and early careers.

Early career scientists frequently engage with their communities to disseminate the knowledge they gained as college students and serve as mentors for younger students. Many Native American college graduates in fact view it as their responsibility to give back to the communities after college (Guillory, 2008; Jaumot-Pascual et al., 2023a, 2023b; Salis Reyes, 2019). These students use the skills they developed in college as foundation to serve their communities in tangible ways, with many efforts dedicated to ensuring tribal sovereignty and prosperity (Brayboy et al., 2012; Jaumot-Pascual et al., 2023a, 2023b; Salis Reyes, 2019). Native American STEM graduates act as "trusted insiders" who can "translate scientific concepts to make them more meaningful for people in the community who do not have scientific training or who might not understand the issues." (Page-Reeves et al., 2019, p 27).

Recently, Wierenga and colleagues (2025) proposed the concept of communities for impact as "spaces to help researchers (especially early-career researchers) cope with the challenges of impact-driven research" (p. 19). Many early career researchers are passionate about high-impact interdisciplinary research that can serve communities and assist in solving global challenges, yet there are institutional barriers in academia that hinder this work (Ferraro et al., 2015; Wierenga et al., 2025). These barriers can include the tenure promotion pipeline, department-specific research funding, and the reality that these issues (such as climate change) could be construed as divisive in this current higher education landscape. The scope and complexity of impact-driven research requires extensive analysis and collaboration that results in fewer publications – a barrier especially challenging for untenured researchers. Communities for impact help empower impact-driven researchers through peer support, networking, and strategizing about their projects. The communities possess the threefold goals of creating community among passionate researchers, legitimizing community-driven research in academia, and alleviating tension between their career advancement and research pursuits (Baudoin et al., 2023; Trinh et al., 2022; Wierenga et al., 2025). These groups can serve as a model for how STEM educators and researchers can build communities that allow students' community engagement pursuits to be recognized and supported both during and after their college years.

Practices for Growth

We can work to advance community engagement within STEM education. These five recommendations center around making communal goals within STEM fields more salient and providing additional opportunities for students to work and learn in community (Boucher et al., 2017; Fuesting & Diekman, 2017; Herrera & Kovats Sanchez, 2022; Joshi et al., 2022; Rendon et al., 2020). Following Bronfenbrenner's (1979, 1994) approach, I first address microsystem-level recommendations and then proceed to discuss beneficial practices at mesosystem and exosystem level. These five recommendations are 1. Celebrate students' communities and cultural backgrounds; 2. Center instruction on how science can address social injustices; 3. Embed communal goals and opportunities within STEM curricula; 4. Leverage learning opportunities of place-based education; and 5. Embrace the promises of citizen science.

Celebrate Students' Communities and Cultural Backgrounds

The first recommendation calls for us to celebrate STEM students' communities and cultural backgrounds. Students bring to STEM departments a wealth of knowledge, resources, and connections to their communities. According to Mwangi and colleagues (2021), there is little literature exploring how STEM students navigate family and school, or how STEM programs affect students' relationships with home. The authors found that many of the participating STEM students' departments "did not build meaningful engagement opportunities within local communities that acknowledge students' motivations for pursuing STEM degrees" (p. 1). Using Yosso's (2005) CCW framework as a guide, educators should celebrate students' cultural backgrounds as an asset that students bring to STEM programs rather than as baggage that holds them back from STEM success (Burt & Johnson, 2018; Denton et al., 2020; Rincon et al., 2020; Rincon & Rodriguez, 2021; Samuelson & Litzler, 2016).

STEM departments can utilize several strategies to achieve this goal. First, departments should recognize the forms of capital that students bring to STEM spaces. For example, Cochran et al. (2025) recently examined physics graduate students' familial capital in order to provide guidance for physics graduate programs. Given that many students cited critical support from family during their programs, the authors recommended that graduate programs structure more opportunities for families to be involved in celebrating students' key milestones such as orientation, passage of comprehensive exams, and department graduations. On the note of celebration, departments can also recognize culturally significant holidays for students and disseminate information about wider campus events that connect to students' cultural backgrounds. Partnerships with student organizations – such as the Association for Women in Science (AWIS) and the National Society of Black Engineers (NSBE) – could likewise be valuable for STEM departments. In short, STEM students should be invited to share about their familial and cultural experiences. We can also center students' aspirational capital in STEM. Upon students' entrance to a STEM program and throughout, faculty should inquire about their motivations for pursuing STEM and seek alignment between course objectives and achieving these goals. Using a culturally responsive approach, instructors can tailor certain aspects of the curriculum to address students' goals.

Center Instruction on How Science Can Address Social Injustices

One of the most persistent misconceptions about the nature of science is that it operates in a vacuum – isolated from social influence and not able to serve broader societal goals (Chalmers, 1976; McComas, 2002; Rubba, 1981). Within STEM curricula, we can center instruction on how science can address social injustices. This recommendation attends to students' desire to advance equity and justice through their science careers and thus improve their perceived congruity between their social justice intentions and future careers (Brown et al., 2015; Diekman et al., 2010; Isenegger et al., 2023; McGee, 2016; McGee & Bentley, 2017; Steinberg & Diekman, 2017).

There are many relevant case studies that STEM educators can embed within their teaching to show students how science can advance social justice aims. For example, the Next Generation Science Standards (2013) outlined a core objective for biology students including HS-LS3: inheritance and variation of traits. In meeting this objective, biology educators might consider a case study of the Human Genome Project – a historic international research effort that resulted in the full sequencing of the human genome and opened the door for more targeted medical treatments. Students can learn about how geneticists and doctors partnered to advance treatments towards sickle cell disease, which remains a debilitating blood disease overrepresented in African American and Hispanic communities (Pace, 2007). Students can also reckon with the reality that these scientific treatments were developed in a context of persistent stigma of the disease in the American public (Bulgin et al., 2018) and discuss how such dynamics would affect the scientific community.

Likewise, a chemistry course could incorporate a case study of the ongoing lead pipe crisis in urban centers during discussion of chemical bonding and aqueous chemistry. Instructors can center the ongoing fight for environmental justice in Flint, Michigan – a municipality outside of

Detroit, USA whose residents have long suffered with high levels of lead in their water as a result of a government decision to switch the local water source to the Flint River without corrosion inhibitors (Campbell et al., 2016). Physics and engineering students can learn principles of community-oriented engineering pedagogy (Rayna, 2022). This pedagogy centers equity and justice in engineering outcomes. Students can not only embed these principles into their future engineering practice but also understand how engineering projects of the past may have not lived up to these ideals. In another example, my hometown of Syracuse, New York is undergoing demolition of Interstate-81 – a substantial elevated highway completed in 1969 that resulted in the destruction of the thriving 15th Ward and served as a dividing line between Black communities and the wealthier urban areas (Teron, 2022). The interstate was a fixture of inequality in the city for decades. In recent years, engineers, officials, and residents have come together to plan removal of the elevated highway in favor of a more equitable community grid plan.

In all these examples, scientists have been key stakeholders advocating for broader communities. STEM disciplines are positioned as pathways through which scientists serve humanity (McGee & Bentley, 2017). Students will develop an understanding of how they capitalize on their social justice intentions through science while maintaining rigorous scientific standards. From a goal congruence perspective, students also learn that there is overlap – and indeed, congruence – between their socially active “selves” and scientific “selves” (Markus & Nurius, 1986). These efforts are likely to have positive downstream effects on students’ interest and retention in STEM (Belanger et al., 2020; Carter et al., 2021; Isenegger et al., 2023; Yu et al., 2025).

Embed Communal Goals and Opportunities within STEM Curricula

The third recommendation calls on STEM departments to make salient the communal goals and opportunities within STEM. The literature shows that students are more likely to persist in STEM if they perceive these disciplines to be collaborative and communal in nature (Diekman et al., 2010; Steinberg & Diekman, 2017). Interestingly, Joshi and colleagues (2022) found that life science departments showcased greater community opportunities for students as compared to natural science departments. The authors found that physics and engineering departments tended to have fewer collaborative assignments or community events advertised within shared department spaces. Thus, all STEM departments – but especially those in the natural sciences – should support initiatives to foster community among students and faculty.

Inside the classroom, collaborative work can be a cornerstone of STEM learning. The scholarship portfolio of mathematician and mathematics educator Dr. Uri Treisman can serve as a guide for fully embedding collaboration within STEM learning. As a doctoral student, Treisman identified that many undergraduate STEM students, particularly those from underrepresented minority communities, struggle in mathematics despite their numerous successes outside the classroom. The existing literature at the time framed these students' struggles as a result of their lack of motivation or family emphasis on education (Triesman, 1992). However, he observed that URM students – especially immigrant students – formed informal social communities to support their learning. In response to his observations and existing literature, Triesman launched the Emerging Scholars Program (ESP) as a way to not only promote camaraderie among students but instill rigorous STEM learning from an asset-based perspective – much like Yosso (2005) would later offer with the CCW framework. At their core, ESPs see students work collaboratively to solve challenging problems in an active learning environment (Fullilove & Treisman, 1990; Treisman, 1992). Peers and instructors embrace their role as facilitators during this process. Treisman's program has been repeatedly shown to improve both URM and non-URM students' performance and persistence in STEM fields at various institutions (Deshler et al., 2016; Hsu et al., 2008; Jamieson et al., 2012; Johnson & Elliott, 2020; Miller et al., 2021). At West Virginia University, 81% of URM students passed an ESP calculus course compared to 50% who passed in a non-ESP calculus course (Miller et al., 2021). These findings indicate that communal STEM learning can advance students' achievement while also supporting their social, aspirational, and navigational capital.

Another viable strategy to improve students' communal perceptions of STEM fields is through exposure to altruistic or community-engaged scientific role models. Morgenroth and colleagues' (2015) Motivational Theory of Role Modeling offers a framework for understanding how role models positively impact students. The scholars put forth three core role model attributes that have such effects on students: perceived similarity to the student, embodiment of success and competence, and achievement of attainable success. Such role models serve to inspire students that they can likewise achieve success, and both observational and experimental research have shown that students perceive higher levels of similarity with scientific role models that work with the public or value altruistic goals (Gladstone & Cimpian, 2021; Marx & Ko, 2012). In STEM curricula, students can learn from these role models in numerous ways such as scientist spotlight assignments (Brandt et al., 2020; Metzger et al., 2023), guest speakers (Casper & Balgopal, 2020), and field trips (Jones & Washko, 2022).

We should not only encourage students to engage with the community outside the classroom, but also eliminate barriers to make it possible for students to participate. Murphy and Kelp (2023) find that STEM students are motivated to pursue community engagement but often lack opportunities to do so. The authors recommend that STEM departments make concerted efforts to engage students with community through interventions such as course-based undergraduate research experiences (CUREs) or k-12 science outreach. To facilitate widespread student participation in such initiatives, departments may consider offering college credit or a stipend for students so that they can financially justify participation. Institutional partnerships with industry, local k-12 schools, and nonprofit organizations will be invaluable to these efforts.

Through these interventions, students can "disrupt stereotypic perception that STEM fields do not provide communal opportunities and foster positivity towards them" (Brown et al., 2018, p. 12). These efforts prompt students' experiences of congruence between their desired communal goals and their STEM education. From a CCW perspective, student engagement in these opportunities outlined above nurtures various forms of capital both in students and faculty.

Leverage Learning Opportunities of Place-Based Education

Place-based education (PBE) refers to the sentiment that education should be rooted in the locations and communities in which they exist, which Deringer (2017) analogizes as community "not stopping at the walls of the schoolhouse" (p. 335) and instead addressing local problems through education (Gruenewald, 2003). PBE is inherently interdisciplinary and acknowledges the various meanings that place has for students, teachers, and community members (Demarest, 2014; Dunbar-Wallis et al., 2024). The advantages of PBE are threefold. The approach promotes synergy between STEM students and their surroundings, which in turn causes students to consider both the unique experiences of living and studying within a place, as well as the potential similarities across cultures and communities (Habig & Gupta, 2021; Raja, 2024). Second, PBE engages STEM students in solving community problems – efforts which tangibly improve the lives of the citizens within. Third, PBE works to decolonize STEM education by centering Indigenous perspectives or "ways of knowing" (Kimmerer, 2013, 2024; O'Neill et al., 2023). Syracuse University – my home institution – maintains ongoing initiatives that support the latter two goals of PBE. Specifically, we are home to the Engaged Humanities Network, a scholarly collective dedicated to advancing community-engaged research within Central New York. One active project is the Food Sovereignty and Seed Rematriation project, led by Dr. Mariaelena Huambachano, whose purpose is to reclaim indigenous food knowledge advanced by the native Onondaga people living in the region. Projects such as these are important to advance STEM students' sense of place as well as expand their understanding of the diversity that scientific research and community engagement projects can take on.

Embrace the Promises of Citizen Science

To fully capitalize on the benefits of community engagement in science, institutions need to facilitate easy and widespread opportunities for community members to engage in the scientific process. As Bronfenbrenner (1979) would suggest, we can work to expand scientific enterprise from an activity within the microsystem to the exosystem of the institution. By doing so, we not only produce greater scientific knowledge (Cohn, 2008; Delaney et al., 2008; Elbroch et al., 2011) but also work to combat the stereotype that science remains an isolated pursuit (Diekman et al., 2010; Nicholls et al., 2007).

Like PBE, citizen science holds tremendous promise in bridging gaps between professional science, STEM education, and the public. Broadly defined, citizen science projects see volunteers partner with professional scientists to answer real-world questions (Citizen Science Central, 2013). The project sponsor – usually a university department or nonprofit – specially designs such projects to give a role to community members. Such roles can range from data collection to data analysis to presentation of results. One of the most prominent ongoing citizen science projects is facilitated by the USGS National Institute of Invasive Species Science (Gallo & Waitt, 2011; Pocock et al., 2024; Silvertown, 2009). Citizens nationwide partner with the Institute to document the presence of invasive species in their local communities, which provides crucial knowledge necessary for their early eradication. Similarly, a recent citizen science project documented 141 native species within US National Parks that had not been previously recorded by the National Park Service (Katzer et al., 2025). Quality citizen science projects are able to maximize the contributions of both the volunteers and professionals, which ultimately work in tandem to advance project aims

(Silvertown, 2009).

Students, higher education institutions, and scientists alike would all benefit from heightened participation in citizen science initiatives. First, students stand to gain significant benefits from citizen science initiatives. Numerous studies indicate that students experience gains in science knowledge (Kermish-Allen et al., 2019), scientific reasoning (Rogele, 2021), science interest (Smith et al., 2021), and civic engagement behaviors (Condon & Wichowsky, 2018) as a result of participation. Second, citizen science represents an open frontier for institutions. By partnering with the public, institutions expand their reach to new communities, which is likely to have positive downstream effects on their quantity of applications, support for future institutional initiatives and participation within, and overall community standing (Dick, 2017). Third, scientists themselves acknowledge the untapped potential of citizen science. Burgess and colleagues (2017) reported that 78% of their scientists surveyed said that their data could be collected by amateurs but only 34% have previously employed citizen scientists. While some scientists believe citizen science data poses validity concerns, this concern can be allayed in light of recent findings (Katzer et al., 2025; Riesch & Potter, 2014). Cohn (2008) examined a McGill University study of New England invasive crab species and found that participating 7th graders possessed a 95% correct observation rate. Additionally, citizen science represents greater democratic participation in the scientific enterprise – challenging the notion that the boundary between science and society is a "semipermeable membrane, through which knowledge only flows outward" (Ziman, 1984, p. 4). In this deficit paradigm, citizens are expected to be informed about scientific developments but also recognize that they do have the expertise to comment on complex decisionmaking (Levison, 2010; Wynne et al., 1995). Rather, a science education as praxis approach sees science as emergent knowledge whose generation deconstructs boundaries between expert and lay knowledge (Levinson, 2010). Participants work towards a common goal, and the status of citizens are elevated to that of citizen scientists or "scientists-in-training". Not only does citizen science promote egalitarian values within science, but it expands the definition of science community to involve all those who engage with science, not just credentialed experts.

Conclusion

This chapter has explored the myriads of ways in which STEM students foster, experience, and redefine community engagement in science. Three theoretical frameworks – Ecological Systems Theory (Bronfenbrenner, 1979, 1994), Goal Congruity Framework (Diekman et al., 2010) and Community

Cultural Wealth (Yosso, 2005) – have demonstrated utility in this pursuit. We see that students' supportive pre-college experiences with family, teachers, and cultural groups establish their "roots" as members of their community. Students' academic and social relationships, coupled with their participation in high-impact science practices, nourish their altruistic STEM career ambitions during college. After college, students emerge as newly-trained scientists ready and able to give back to the community. These empirical findings led me to offer five practices for growth for researchers and educators looking to capitalize on what Brown and colleagues (2018) deem this "new vantage point" for STEM education (p. 21). Following Bronfenbrenner's (1979) approach, these recommendations center different systems (and therefore different units of analysis) to celebrate and leverage the opportunities for community engagement in STEM education. Researchers, educators, students, and citizens alike can collaborate to fully capitalize on the potential for STEM community engagement.

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Chapter 8

Educating Responsible Innovators: Ethical Consideration in STEM Education

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Chapter Highlights

Ethical considerations in STEM education are increasingly important as technology shapes contemporary society. Integrating ethics into STEM curricula enables students to address global challenges while evaluating the societal implications of innovation. Through principles such as equity, collaboration, critical thinking, and inclusivity, ethics education supports responsible and socially aware STEM practices.

- Foundations of Ethical STEM Education – Emphasises core principles such as equitable access, inclusivity, teamwork, critical thinking, and responsible innovation as the basis of ethical STEM practice.
- Curriculum and Interdisciplinary Integration – Explores strategies for embedding ethics across STEM curricula, supported by collaboration with the humanities and the integration of professional and industry ethical standards.
- Ethics of Emerging Technologies – Examines ethical challenges related to artificial intelligence, biotechnology, nanotechnology, and genetic engineering, highlighting the need for forward-looking ethical frameworks.
- Global and Societal Challenges – Applies ethical reasoning to real-world problems such as climate change, healthcare equity, and technological inequality, linking STEM education to societal responsibility.
- Critical Thinking and Ethical Decision-Making – Focuses on developing students' ethical reasoning skills through case studies, moral dilemma analysis, and structured decision-making frameworks.

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Introduction

Ethical considerations in STEM education are becoming more important as technological advancements continue at an accelerating pace. This paper addresses the imperative need to integrate ethics and social responsibility into STEM curricula, preparing students to tackle complex global challenges while considering the ethical implications of their innovations (Bencze & Alsop, 2014; Mitcham & Englehardt, 2019).

At its core, ethical STEM education encompasses a framework that promotes fair access, teamwork, critical thinking, and inclusivity (Bencze & Alsop, 2014). By establishing these principles, educators aim to develop students who can balance innovation with social responsibility, ultimately contributing to a more equitable and sustainable future (Canney & Bielefeldt, 2016). The integration of ethics into STEM education goes beyond standalone courses, requiring a multifaceted approach that weaves ethical considerations throughout the curriculum (Zandvoort et al., 2013). This holistic strategy enables students to develop a nuanced understanding of the ethical dimensions inherent in scientific and technological progress (Bencze & Alsop, 2014; Zandvoort et al., 2013).

Implementing ethical STEM education presents several challenges, including the need to balance technical skill development with ethical reasoning, addressing diverse perspectives, and keeping pace with rapidly evolving technologies (Weckert & Moor, 2006). However, these challenges also present opportunities for educators to create dynamic, interdisciplinary learning experiences that prepare students for the complex ethical landscape they will navigate in their future careers (Zandvoort et al., 2013).

By emphasizing ethical considerations in STEM education, institutions can cultivate a generation of responsible innovators who approach their work with a balanced understanding of the societal implications of their actions (Bencze & Alsop, 2014; Mitcham & Englehardt, 2019). This approach not only enhances students' critical thinking and problem-solving skills but also equips them with the emotional intelligence required to navigate ethical dilemmas in their future STEM careers (Bencze & Alsop, 2014; Zandvoort et al., 2013).

Foundations of Ethical STEM Education

The foundations of ethical STEM education are built on core principles that aim to create responsible, socially aware innovators. These principles include fair access, teamwork, critical thinking, and inclusivity (Bencze & Alsop, 2014). By emphasizing these values, educators can create an environment where students learn to balance innovation with social responsibility, a crucial skill in today's rapidly evolving technological environment.

Central to this foundation is the development of a robust framework for ethical decision-making in STEM. Such frameworks provide students with the tools to successfully negotiate complex ethical dilemmas they may encounter in their careers. These decision-making models often incorporate elements of consequentialism, deontology, and virtue ethics, allowing students to approach problems from multiple ethical perspectives.

Integrating ethics into STEM curricula requires a delicate balance between technical knowledge and ethical reasoning. Waghid (2014) argues that this integration should not be viewed as an add-on but as an essential component of STEM education. This approach helps students understand that ethical considerations are intrinsic to the scientific process and technological development, rather than a tacked-on afterthought.

The foundation of ethical STEM education emphasizes the importance of interdisciplinary learning. By drawing connections between STEM fields and humanities subjects like philosophy, sociology, and psychology, students can develop a more holistic understanding of the ethical implications of their work (Børsen et al., 2021). This interdisciplinary approach helps bridge the gap between technical expertise and ethical awareness. Moreover, the foundation of ethical STEM education recognizes the need for continuous adaptation. As new technologies emerge and societal values evolve, the ethical landscape shifts to keep pace. Therefore, a key aspect of this educational foundation is instilling in students the ability to engage in lifelong learning and ethical reflection (Mitcham & Englehardt, 2019).

By establishing these foundations, STEM education can produce work-ready graduates who are not only technically proficient but also ethically conscious and socially responsible. This is a holistic approach to STEM education that is crucial in enabling the next generation of innovators to address global challenges while considering the broader implications of their work.

Integrating Ethics into STEM Curricula

Integrating ethics into STEM curricula is a challenge that requires thoughtful strategies and innovative approaches. This integration is important for cultivating students who can operate in the complex ethical landscape of modern scientific and technological advancements (Mitcham

& Englehardt, 2019).

One effective strategy for incorporating ethical discussions in STEM classes is the use of case studies and real-world examples. These provide concrete scenarios that allow students to apply ethical reasoning to practical situations. For instance, Zandvoort et al. (2013) describes how engineering ethics can be taught through analysis of historical cases, such as the Challenger disaster or the Deepwater Horizon oil spill. This approach helps students understand the real-world consequences of ethical decision-making in STEM fields.

Interdisciplinary approaches are also key to successful ethics integration in STEM curricula. Børsen et al. (2021) argue that collaboration between STEM departments and humanities faculties can create more comprehensive ethical education. This might involve team-teaching between ethics professors and STEM instructors, or the development of courses that explicitly bridge technical and ethical content. Another effective method is the incorporation of ethical considerations into existing STEM projects and assignments. Rather than treating ethics as a separate subject, it can be integrated into technical coursework. Engineering design projects should therefore include explicit ethical analysis components, encouraging students to think about the social impacts of their designs right from the beginning.

The use of interactive teaching methods, such as role-playing exercises or debates, can also enhance ethical learning in STEM education. These methods encourage students to engage actively with ethical dilemmas and consider multiple perspectives (Waghid, 2014).

Moreover, the integration of ethics into STEM curricula should be supported by appropriate assessment methods. Bencze and Alsop (2014) point to the importance of evaluating not just technical knowledge, but also ethical reasoning skills and the ability to recognize and address ethical issues in STEM contexts. By employing these strategies, educators can create a STEM curriculum that not only imparts technical knowledge but also develops ethically aware and socially responsible professionals.

Addressing Global Challenges through Ethical STEM

The integration of ethics into STEM education is vital for equipping students with the skills and mindset necessary to finding solutions to pressing global challenges. This approach recognizes that scientific and technological advancements must be guided by ethical considerations to ensure positive outcomes for society and the environment.

Climate change and environmental sustainability represent key areas where ethical STEM education can make an impact. Arguably, STEM curricula should incorporate sustainability principles, enabling students to develop innovative solutions while considering the long-term environmental consequences. This approach engenders a sense of responsibility towards the planet and encourages the development of green technologies and sustainable practices.

In the areas of healthcare and bioethics, ethical STEM education plays a vital role in preparing future professionals to successfully negotiate complex moral dilemmas. Rapid advancements in biotechnology and medical research raise many ethical questions. By integrating bioethics into STEM curricula, students can develop the critical thinking skills needed to balance scientific progress with ethical considerations in areas such as genetic engineering, stem cell research, and personalized medicine.

Artificial Intelligence (AI) and data privacy presents another critical area where ethical STEM education is essential. Floridi and Cowls (2019) emphasize the need for AI developers to consider the ethical implications of their work, including issues of bias, transparency, and privacy. By incorporating these ethical considerations into STEM education, students can learn to design AI systems that respect human rights and while promoting benefits to society. Ethical STEM education also plays a crucial role in addressing issues of global inequality and access to technology. Marginson (2020) argues that STEM education should aim for a sense of global citizenship, encouraging students to consider how their innovations can benefit underserved populations and reduce technological disparities between nations.

By addressing these global challenges through an ethical lens, STEM education can produce graduates who are not only technically proficient but also socially conscious and ethically responsible. This approach is crucial for developing solutions that are not only innovative but also sustainable, equitable, and beneficial to society as a whole.

Ethical Implications of Emerging Technologies

Emerging technologies like biotechnology and genetic engineering stand at the forefront of ethical debates in STEM. As Greely (2019) notes, technologies like CRISPR gene editing offer unprecedented capabilities to alter the human genome. This raises profound questions about the limits of human intervention with the processes of Nature. STEM curricula need to equip students with the ethical frameworks to consider issues such as designer babies, genetic enhancement, and the potential for creating new forms of inequality based on genetic modification.

Nanotechnology and materials science present another broad area of ethical challenge. Weckert and Moor (2006) highlight concerns about the potential environmental and health impacts of nanoparticles, as well as issues of privacy and security that could arise from nano-scale sensors. Ethical STEM education in this field must build awareness of the precautionary principle and the importance of rigorous safety testing in the development of new materials.

Robotics and machine learning also raises ethical questions about the future of work and human-machine interaction. The rapidly increasing sophistication of AI and robotics could lead to significant job displacement, requiring STEM graduates to consider the societal impacts of their innovations. The development of autonomous systems, particularly in contexts like warfare or eldercare, also presents complex ethical dilemmas that students need to be prepared to address. Ethical considerations in these emerging fields often intersect with broader social issues. For instance, the potential for these technologies to exacerbate existing inequalities or create new forms of discrimination must be a key consideration in STEM education. As Jasanoff (2016) argues, responsible innovation requires a deep understanding of the social and political contexts in which technologies are developed and deployed.

Moreover, the rapid pace of technological change means that ethical frameworks must be adaptable and forward-thinking. STEM education should therefore not only focus on current ethical issues but also cultivate in students the ability to anticipate and address future ethical challenges that may arise from emerging technologies.

A Mindset of Responsible Innovation

As discussed in earlier sections, responsible innovation is an important component of ethical STEM education. It is imperative to produce graduates who know how to balance technological advancement with societal benefits and ethical considerations. This calls for a multifaceted strategy that includes user-centered and ethics-centered design principles, balancing commercial demands with societal benefits, and promoting academic honesty and research integrity. User-centered and ethics-centered design principles therefore form the cornerstone of responsible innovation. As von Schomberg and Blok (2019) argue, these approaches ensure that technological developments are aligned with societal needs and values from the outset.

STEM curricula should incorporate methodologies that encourage students to consider the end-users and broader societal impacts of their innovations throughout the design process. This includes teaching techniques for stakeholder engagement and participatory design, which can help identify potential ethical issues early in the development cycle.

Balancing commercial demands with societal benefits is a significant challenge in responsible innovation. Stilgoe et al. (2013) emphasize the importance of teaching students to deal with the often-conflicting pressures of market forces and ethical considerations. STEM education should equip students with the tools to conduct thorough cost-benefit analyses that include not just financial metrics, but also social and environmental impacts. Case studies of successful responsible innovations can provide valuable insights into how this balance can be achieved in practice.

Critical Thinking and Problem-Solving Skills

Developing critical thinking and problem-solving skills is foundational in ethical STEM education, as these competencies enable students to deal with complex ethical dilemmas and make informed decisions. This aspect of STEM education focuses on equipping students with ethical frameworks for decision-making, enhancing their ability to analyze ethical dilemmas, and promoting independent thought and ethical reasoning. Such frameworks provide students with structured approaches to addressing moral challenges in STEM fields. Ideally, these frameworks should include a variety of ethical theories such as utilitarianism, deontology, and virtue ethics.

By exposing students to multiple ethical perspectives, STEM education can create a nuanced understanding of moral reasoning. For instance, the framework proposed by Harris et al. (2013) for engineering ethics education emphasizes the importance of considering multiple stakeholders and long-term consequences in ethical decision-making.

Analyzing ethical dilemmas in STEM contexts is a crucial skill that requires practice and guidance. Zandvoort et al. (2013) suggest using case studies and real-world scenarios to help students apply ethical frameworks to concrete situations. This approach not only enhances students' analytical skills but also demonstrates the relevance of ethics to their future professional practice. Moreover, engaging students in ethical analysis of emerging technologies can help them anticipate and address ethical challenges in their fields going forward.

Promoting independent thought and ethical reasoning is fundamental to developing critical thinking skills in STEM education. Mitcham and Englehardt (2019) emphasize the importance of encouraging students to question assumptions and critically evaluate the ethical implications of scientific and technological advancements. This can be achieved through techniques such as Socratic questioning, ethical debates, and reflective writing exercises that prompt students to articulate and defend their ethical positions. In addition, integrating problem-based learning approaches, as described by Savery (2006), can enhance students' ability to apply ethical reasoning to complex, real-world problems. This method challenges students to identify ethical issues, gather relevant information, and develop solutions that balance technical feasibility with ethical considerations.

Developing metacognitive skills is also important for enhancing critical thinking in ethical contexts. As noted by Tanner (2012), encouraging students to reflect on their own thinking processes can improve their ability to recognize biases and enhance the quality of their ethical reasoning.

By focusing on these aspects of critical thinking and problem-solving, STEM education can thus produce graduates who are not only technically proficient but also ethically aware and capable of working in the complex moral landscape of modern science and technology. It ensures that future STEM professionals are able to make responsible decisions that consider both the technical and ethical dimensions of their work.

Preparing Students for Ethical Challenges in the Workforce

Bridging the gap between academia and industry is essential for ensuring that students are prepared for real-world ethical challenges. Colby and Sullivan (2008) argue that STEM curricula should incorporate industry partnerships and internships that expose students to authentic ethical dilemmas in professional settings. These experiences can provide valuable context for classroom learning and help students understand the practical application of ethical principles. Inviting industry professionals to participate in ethics courses or workshops can offer students insights into the ethical challenges they may encounter in their future careers.

Developing ethical leadership skills is necessary to prepare students to deal with complex ethical landscapes in the workforce. Arguably, ethical leadership in STEM fields requires not only the ability to recognize ethical issues but also the skills to guide teams and organizations towards ethical decision-making. STEM education should therefore incorporate leadership training that emphasizes ethical considerations, including modules on ethical communication, conflict resolution, and fostering an ethical organizational culture.

Being committed to continuous learning and adaptation to evolving ethical issues is vital in a rapidly changing technological landscape. Mitcham and Englehardt (2019) emphasize the importance of instilling in students a recognition that ethical challenges will continue to evolve throughout their careers. STEM curricula should therefore focus on developing students' skills in ethical foresight and adaptability. This can be achieved through exercises in scenario planning and ethical impact assessment of emerging technologies.

The integration of professional codes of ethics into STEM education is another crucial aspect of workforce preparation. Harris et al. (2013) suggest that students should be familiarized with relevant professional codes and taught how to apply these guidelines in practical situations. This approach helps students understand the ethical expectations of their chosen professions and prepares them to navigate potential conflicts between personal, professional, and organizational ethics. Also, preparing students for ethical challenges in the workforce requires addressing the global nature of many STEM careers. Zandvoort et al. (2013) argue that STEM education should include consideration of cross-cultural ethical issues and the challenges of working in diverse, international teams. This global perspective can help students develop the cultural sensitivity and ethical flexibility needed in today's interconnected world.

STEM education should emphasize the importance of ethical advocacy in the workplace. Canney and Bielefeldt (2016) suggest that students should be trained in strategies for effectively raising ethical concerns and promoting ethical practices within their organizations. This includes developing skills in ethical argumentation and understanding the processes for ethical decision-making within corporate structures. By focusing on these aspects of workforce preparation, STEM education can produce graduates who are not only technically proficient but also ethically competent and prepared to face the complex moral challenges of their professional lives. This comprehensive approach ensures that future STEM professionals are equipped to make responsible decisions and contribute positively to their fields and society at large.

Conclusion

This chapter has made the case for integrating ethical considerations into STEM education. It represents a critical imperative for preparing the next generation of responsible innovators. This comprehensive examination demonstrates that ethical STEM education is not merely an academic exercise but a fundamental necessity for addressing the complex challenges facing our STEM graduates as they make their way into the workforce.

The evidence presented throughout this paper emphasizes the urgent need for a holistic approach to ethics integration that goes well beyond standalone courses. The most effective strategy involves weaving ethical considerations throughout the entire STEM curriculum, ensuring that students develop an intrinsic understanding of the moral dimensions inherent in scientific and technological advancement. This integration must be grounded in core principles of fair access, teamwork, critical thinking, and inclusivity, creating a foundation for responsible innovation that balances technical proficiency with social responsibility.

The practical implementation strategies outlined—including case studies, interdisciplinary collaboration, and interactive teaching methods—provide concrete pathways for educators to embed ethical reasoning into their teaching practice. These approaches are particularly crucial when addressing global challenges such as climate change, healthcare inequities, artificial intelligence governance, and emerging biotechnologies. The ethical implications of technologies like CRISPR gene editing, nanotechnology, and autonomous systems require students to grapple with complex questions about human enhancement, environmental impact, and societal disruption that will define their professional careers.

Perhaps most significantly, this analysis reveals that ethical STEM education must cultivate critical thinking and problem-solving skills that enable students to successfully negotiate novel moral landscapes. The development of ethical frameworks for decision-making, combined with the ability to analyze complex dilemmas from multiple perspectives, prepares students to confront challenges that cannot be anticipated through traditional technical training alone. This capability becomes even more important as the pace of technological change accelerates and ethical considerations become increasingly nuanced.

The workforce preparation dimension highlighted throughout this chapter emphasizes the practical urgency of these educational reforms. Future STEM professionals will operate in environments where ethical leadership, cross-cultural sensitivity, and the ability to advocate for responsible practices are not optional competencies but essential professional skills. The integration of industry partnerships, professional codes of ethics, and real-world case studies ensures that academic learning translates effectively into professional practice.

Looking forward, the most important conclusion emerging from this analysis is that ethical STEM education must embrace adaptive thinking and continuous learning. As new technologies emerge and societal values evolve, the ethical landscape will continue to shift in ways that cannot be fully predicted. Therefore, the ultimate goal of ethical STEM education is not to provide students with fixed answers but to develop their capacity for ongoing ethical reflection and responsive innovation.

The way forward requires commitment from educational institutions, industry partners, and policymakers to prioritize ethical considerations as equal partners with technical competence. Only through this comprehensive approach can we ensure that the remarkable capabilities of STEM fields are channeled toward creating a more equitable, sustainable, and ethically sound future for all.

Recommendations

Go beyond standalone ethics courses to integrate ethical considerations throughout all STEM curricula. This should treat ethics as an intrinsic component rather than a 'nice-to-have' afterthought. This will ensure students understand that ethical reasoning is fundamental to scientific and technological progress.

Also recommend to use real-world case studies and historical examples (such as the Challenger disaster or Deepwater Horizon oil spill) to provide concrete scenarios for applying ethical frameworks. This approach helps students understand the practical consequences of ethical decision-making in professional contexts.

Cultivate partnerships between STEM departments and humanities faculties to create comprehensive ethical education programs. Team-teaching approaches between ethics professors and STEM instructors can bridge technical expertise with ethical awareness. Integrate ethical analysis components into existing technical projects and assignments, encouraging students to consider social impacts from the design phase. This approach ensures ethics becomes embedded in the problem-solving process rather than treated as a separate consideration.

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Chapter 9

STEM Education and Environmental Sustainability

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Chapter Highlights

This chapter summary provides the reader with a quick overview, summarizing the key points from the chapter addressing STEM education and environmental sustainability.

- Essential Components of STEM Education – It combines science, technology, engineering and mathematics in an interdisciplinary manner.
- Environmental Sustainability Context – STEM has an important role in finding solutions to environmental problems such as climate change, biodiversity loss and resource depletion.
- Impact on Learning Outcomes – STEM-based sustainability projects improve students' academic achievement, environmental awareness, problem-solving and critical thinking skills.
- Pedagogical and Applied Approaches – Methods such as project-based learning, the maker movement, nature-based learning and outdoor laboratories are integrated with STEM and sustainability.
- Future Directions and Recommendations – The integration of technologies such as artificial intelligence, big data and IoT into education, curriculum reforms, teacher training and the dissemination of school-based sustainability practices are important steps towards the future in education.

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Introduction

The complexity of the environmental and social dimension of global issues on climate change, biodiversity loss, depletion of natural resources in such a short time and environmental degradation has increased as ever today. As such, these challenges for practitioners need to be tackled not only through conventional methods of education but also demand interdisciplinary and holistic approaches (Christie et al., 2015). To this end, it provides students with scientifically thinking and a more sensitive attitude toward environmental issues (Rahmadayanti & Fielardh, 2024).

In recent years, STEM education has become the focus of education policies of many countries. This approach usually stands out in order to support economic development and increase global competition (Xie et al., 2015). However, it is known that STEM practices that focus only on economic benefits are not sufficient in producing sustainable solutions to today's environmental and social problems. Therefore, integrating STEM education with the understanding of environmental sustainability is seen as an important issue for educators and administrators (Han et al., 2022). Gaining an understanding of environmental sustainability helps students understand nature-related systems, recognize problems and develop solutions (Christie et al., 2015). When this approach is combined with STEM education, students can effectively use many skills from scientific thinking to engineering design, technological tool use to mathematical analysis to solve environmental problems (Istiana et al., 2023).

This study reveals the relationships between STEM education and environmental sustainability; presents a theoretical framework for how these two fields can be integrated and provides information on possible application areas. Thus, it is revealed how the relationship between STEM education and environmental sustainability is shaped at what points. In addition, this section includes detailed evaluations on the future development of the subject, its applicability and effects in various situations.

Definition and Importance of STEM Education

What is STEM?

STEM refers to the fields of science, technology, engineering and mathematics within an educational system. Disciplinary integration was initially proposed by Judith Ramaley (2001) in the field of education in USA, and the studies focusing on the integration of these fields have been gaining speed recently (Roehrig & Karışan, 2022). STEM pedagogy teaches students to develop creative, realistic responses to complex social and environmental problems, with an integrated approach to various branches of science together (Kennedy & Odell, 2014).

In recent years, there has been a dramatic increase in the volume of research on STEM education. This has largely been an experimental and descriptive content, both identifying the training processes to teachers, and their success on the other hand regarding their students (Daşdemir et al., 2018; Karaşah-Çakıcı et al., 2021; Suherman et al., 2025). There is international literature on the integration of STEM and other fields. Researches have shown that projects based on real-life problems, engineering design processes and learning opportunities that involve different disciplines are very valuable for students (Bryan et al., 2015). It is mentioned that integrated STEM projects raise student engagement, reinforce students' ability to apply and transfer knowledge protean, and allow them to learn distinct domains concurrently and more effectively (Capraro et al., 2013).

According to Holmlund et al. (2018) STEM education is the learning of using the fields of science, technology, engineering and mathematics together to solve a problem one faces in everyday life. In this respect, it can thus be claimed that students not only learn about these disciplines but also promote their interdisciplinary thinking skills. Similarly, according to Akgündüz et al. (2015), STEM represents a type of educational approach in which students learn how the knowledge they have acquired through various domain disciplines fits together as a whole and apply this knowledge to resolve the problems in their real life.

STEM education maintains a disciplines based common framework and allows a holistic based learning which is truly connected with life. By this means the students look at a complex problem from various angles (Hasanah, 2020). The application of scientific methods in the learning process enables students to acquire experience of creation of solutions of real-world problems (Savage et al., 2008). In contrast, design thinking opens up the space for creative ideas, builds prototypes of best-practice examples, and rigorously tests those prototypes (Lin et al., 2021). In addition, STEM projects carried out with group work improve students' communication skills. These projects also make it easier for students to adopt leadership roles and work together (Shamuganathan, 2023).

The Interdisciplinary Nature of STEM

The prominent feature of STEM education is that it considers fields such as science, technology, engineering and mathematics as a whole. This approach aims to develop students' creative thinking, critical analysis and problem solving skills (Akarsu et al., 2020). For example, science teaches observation, hypothesis formation and experiment design (Zhan & Niu, 2023). Technology shows ways to collect information, analyze and present data (Yaşar-Ekici et al., 2018). Engineering makes solution production systematic and improves design-oriented thinking (Aşık et al., 2017). Mathematics strengthens numerical thinking and supports solution processes in other disciplines (Bulut et al., 2024).

The interdisciplinary nature of STEM gives students the habit of thinking about information obtained from different fields together. Thanks to this approach, students develop not only their technical skills, but also their ability to think creatively, critically evaluate and create multifaceted solutions to complex problems (Akarsu et al., 2020). Since real-life problems usually involve more than one variable, students' ability to evaluate different aspects at the same time makes it easier for them to analyze the situation more accurately. On the other hand, in STEM projects, students develop themselves not only with academic knowledge, but also with social skills such as working together, exchanging ideas and communicating effectively (Bybee, 2013).

21. Century Skills and STEM

Today's rapidly changing technological structure and the global interaction environment expect individuals to have not only technical knowledge, but also multidimensional skills such as digital literacy, critical thinking, effective communication, creative thinking and working together (Holmlund et al., 2018). STEM education increases the ability of students to analyze complex situations they face and develop solutions (Nguyện et al., 2025), at the same time supports innovative thinking through design-based applications (Sarikoc & Ersoy, 2022). In addition to giving students the habit of acting as a team, group studies conducted during this process also help students to share their thoughts and communicate effectively by understanding each other (Savage et al., 2008; Akarsu et al., 2020). In addition, thanks to the active use of digital tools, students become not only consumers of technology but also conscious and productive users (Yaşar-Ekici et al., 2018).

The basis of STEM activities is for students to gain the skills of analyzing problems that they may encounter in real life, structuring the solution process in a planned way and developing effective solutions. In this process, where critical thinking is used actively, students not only repeat ready-made solutions but also become more effective in developing creative ideas. On the other hand, STEM projects often require teamwork, which is important for students to develop their social skills such as working together, exchanging ideas and achieving common goals (Yıldırım & Altun, 2015). These skills acquired through STEM not only contribute to individual success; they also contribute to the process of producing solutions to problems encountered at the societal level (Han et al., 2022). Therefore, associating the STEM approach with broad-ranging issues such as environmental sustainability can both support individual consciousness development and contribute to the general benefit of society.

Introduction to Environmental Sustainability

The Concept of Sustainability

The sustainability concept defined by the Brundtland Commission in 1987 indicates meeting present needs without compromising the ability of future generations to meets their own (Christie et al., 2012). This definition highlights the need to address both its environmental and social/economic components when considering sustainability. The study of Demirel and Sungur (2018) noted together with the environment, society and economy, sustainability in education should be regarded as well. Furthermore, education are important to provide environmental consciousness and sustainable lifestyle that can include in education materials (Gülersoy & Civil, 2023).

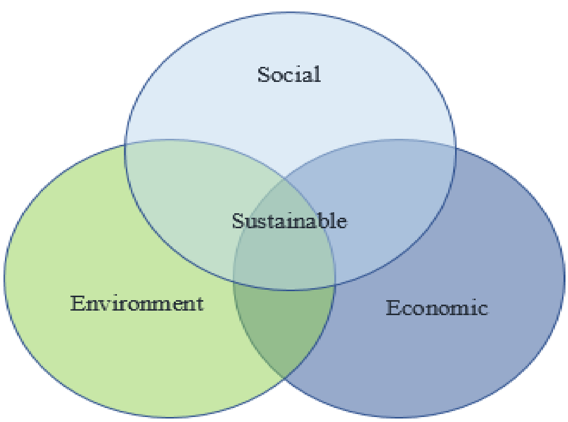

Figure 1. Interaction between the environmental, social and economic dimensions of sustainability (Purvis et al., 2019)

In international literature, the integration of environmental education and STEM is now starting to gain some attention (González-Gómez et al, 2021; Guzmán-Cedhalla et al., 2020). It has been observed that the E-STEM (Environmental-STEM) approach is effective in raising student environmental awareness and thus increases the probability of adopting environmentally sensitive behavior (Helvaci & Helvaci, 2019). In other study Malecha (2020) investigated the STEAM approach which integrated education for the environment and art shows that this integration increased creativity and environmental awareness of students. The basics of sustainability consist of three dimensions: environmental sustainability, social sustainability and economic sustainability. Figure 1 shows the dimensions of sustainability and the interaction between them:

Environmental Sustainability

Environmental sustainability, as an understanding that allows people to exist in a balanced way with nature, aims to support the continuity of the planet's ecosystems without disturbing them. This means maintaining the conditions necessary for natural systems (climate, water cycles, biodiversity etc.) to be self-renewing. The main purpose here is to manage natural resources in a way that is sensitive to the needs of today's and future generations, without depleting them. Sustainability refers to the appropriate utilization of natural resources to keep ecosystems viable (Rockström et al, 2009).

There are four components of environmental sustainability. These are: the sustainable production of clean energy, conservation of biodiversity, the sustainable use of resources and sustainable management of natural systems. Arguably the most vital step to decrease the impacts of climate change, espacially global warming is to decrease the carbon emissions from energy generation and utilization together with implementation of carbon capture technologies (Warszawski et al., 2021). On the other hand, conservation of biodiversity and sustainable use of resources and proper water and land planning, helping to maintain healthy ecosystems and food security is another critical situation in this context (Foley et al., 2011; Cardinale et al., 2012; Kirchherr et al., 2017).

Social Sustainability

Social sustainability is a social paradigm in which people show the ability to meet their needs and have their rights covered. It is a structure that enables people to participate in decision-making. Having such aspects of social and cultural identities in place naturally creates a social structure that also enriches the idea of the individual in the society hence, it is based on recognition of other vital cultural identities and contributes to building the society (Eizenberg & Jabareen, 2017). The theory of social sustainability is in equality, justice and social inclusiveness. This theory aims to narrow the gap in income, opportunity and identity among people (Boström, 2012). It is crucial for all people to have access to healthcare, live in a clean environment, and live in safe living conditions. These are crucial issues that impact individuals' physical and mental health (Vallance et al., 2011). Furthermore, individuals' ability to have a say in decisions that directly affect their lives should be supported through democratic participation processes (Agyeman & Evans, 2004). Lifelong activities, particularly in education, enhance individuals' knowledge and skills related to sustainability while also strengthening the abilities needed for social cohesion and innovative solutions (UNESCO, 2017).

Economic Sustainability

Economic sustainability means conducting economic activities in a way that does not harm human, environmental, or social well-being. It is the concept of prosperity for few in the long view at the expense of many. Nature and social justice must not be trampled by economic systems and actions. Financial sustainability is only one part of economic sustainability. That also means more sharing in wealth, and sharing in our resources so that our resources will last for the generations to come. It is about sustainable, equitable prosperity — not endless growth (Daly, 2005).

While the transition from fossil fuels to clean energy is a crucial issue for the environment and sustainability, it is crucial that the emergence of new job opportunities during the transition does not exacerbate differences between social classes (Ürge-Vorsatz et al., 2014). Sustainable production and consumption patterns are a key element in reducing the negative impact of economic activities on the environment. Similarly, sustainable production and consumption practices have a positive impact on people's quality of life (Geissdoerfer et al., 2017). Beyond existing approaches to measuring economic growth, wealth, and well-being, more comprehensive measurement methods that encompass different dimensions are needed (Costanza et al., 2009).

Environmental Issues and the Role of STEM

In this century, humanity has faced serious environmental issues including climate change, biodiversity loss, deforestation, global warming or ocean acidification and resources depletion of natural water. This gets the natural cycle out of whack and destroys peoples' quality of life. The problem has become so large and expansive that it is going to take the collective work of multiple fields to help solve this. It is essential to approach the problem from a scientific paradigm, integrating technological innovations, engineering perspectives, and mathematical analysis. Environmental problems profoundly impact not only nature but also economic structures and social life. Due to the multifaceted impact and magnitude of the issue, national and international cooperation is crucial in developing strategies for a sustainable future (United Nations, 2022; IPCC, 2023).

In this respect, STEM education enables students to become aware of environmental issues and develop innovative solutions. Through this process, they are able to develop practical ideas around environmental problems applying scientific thinking, problem solving and design skills. While science helps understand natural events and the functioning of ecosystems, fields such as climate change, ecology and environmental chemistry play a fundamental role in helping students understand environmental systems better (Christie et al., 2015). In technology, students are allowed to develop solutions and designs to environmental issues. In this regard, renwable energy, ecofriendly materials, waste and environmental monitoring tools is prominent (Bărbulescu et al., 2025). Students with an engineering background can support their ideas in producing ecological designs that do not destroy the environment (Han et. al., 2022). Mathematical model is employed to comprehend complex environmental processes and to generate future scenarios. Models, especially those related to climate systems and ecosystems, are very effective in predicting the risks that may be encountered (Li et al., 2013).

Connection with the United Nations Sustainable Development Goals

In 2015, the United Nations set the post-2015 Sustainable Development Goals (SDGs) for global sustainable development with specific targets and indicators to be achieved by 2030 (United Nations, 2015). Here, there are 17 global goals under the banner of Sustainable Development Goals (SDGs) and targets stated in a variety of areas from poverty to quality education, gender equality to clean energy and combating climate change through sustainable cities and conservation on land and sea. They fully account the environment, economy and social development. It allows for countries to pursue more fair, equal, and sustainable plans of development (Sachs et al., 2019). It is an objective that must unite all parties both public sector and civil society organization and citizens. Doing so will contribute to a planet that is able to develop in ways that are more efficient, strategic and effective (Griggs et al., 2013). This highlights that sustainability is a question of both ecology but also people and economy (Sachs et al., 2019).The visual for the United Nations Sustainable Development Goals (SDGs) icons is presented in Figure 2.

Figure 2. United Nations Sustainable Development Goals (SDG) icons (United Nations, 2015).

STEM education plays an important role in the implementation of many of the SDGs. Some of the SDGs directly associated with STEM are as follows:

SDG 4 - Qualified Education: STEM education contributes to quality education by providing students with the skills required by the era, such as critical thinking, problem solving, collaboration and effective use of technology (Bybee, 2013; UNESCO, 2021).

SDG 6 – Clean Water and Sanitation: Issues such as efficient and sustainable management of water resources, monitoring of water quality and development of treatment systems are among the main areas where knowledge and skills in STEM fields are applied (UNESCO, 2021).

SDG 7 – Affordable and Clean Energy: Topics such as the design of renewable energy systems, energy efficiency applications and energy storage solutions are technology and engineering-based studies in which STEM education is strong (UNESCO, 2021).

SDG 11 – Sustainable Cities and Communities: Many projects that support sustainable urban life, such as smart city applications, environmentally friendly transportation systems and green building designs, require the collaboration of different STEM disciplines (UNESCO, 2021).

SDG 13 - Climate Action: STEM education helps to understand climate change and develop solutions in this area. Environmental monitoring technologies and climate modeling are concrete examples of this process (Anderson, 2013).

SDG 14 – Life Below Water & SDG 15 – Life on Land: Protecting natural life, sustaining biodiversity and monitoring ecosystems is possible through environmental studies conducted with STEM. (Rockström et al., 2009; UNESCO, 2021).

The Interaction Between STEM Education and Sustainability

Scientific Literacy for Sustainable Development

Scientific literacy has been defined as the extent to which one is able to read and understand science, including using that knowledge to make informed decisions about everyday life (Holmlund et al., 2018). "It's really important that people can do this because so many of the big environmental issues are becoming more complex and you need to be able make good judgments based on good science." However, scientific literacy goes beyond mere knowledge. Scientific literacy encompasses not only the acquisition of knowledge but also the application of that knowledge to daily life and the adoption of sustainable lifestyles. With these characteristics, scientific literacy enables individuals to be more sensitive and solution-oriented to global problems such as environmental pollution, climate change, and biodiversity loss (Vijayatheepan, 2023). STEM education offers a multidimensional perspective and contributes to the development of scientific literacy. This approach has several key components:

Scientific Process Skills: The goal is to equip students with skills fundamental to science, such as observation, prediction, hypotheses, design of experiments, and analysis. Students will develop these skills while being encouraged to be more scientific in their thinking through a series of STEM-based activities. Furthermore, these practices not only improve procedural skills but are also linked to students' academic success (Gürsoy et al., 2023).

Evidence-Based Thinking: Hasanah (2020) states that STEM education facilitates students in honing their skills in decision-making, such as analyzing scientific data and scientific information and supporting these with reliable evidence. Thanks to these skills, students can recognize information pollution, especially in issues related to the environment, and make evaluations based on the right sources.

Systems Thinking: Environmental problems often arise when many interconnected factors come together. To cope with such problems, individuals are expected to have a mindset that can understand the relationships between systems. Demssie et al. (2023) state that systems thinking plays an important role in achieving sustainability. Different practices help individuals not only to gain knowledge, but also to grow up as individuals who can use knowledge effectively.

Coping with Uncertainty: Scientific knowledge is not static; it is constantly renewed and developed. STEM education develops students' ability to make decisions in uncertain situations and act with incomplete information (Christie et al., 2012).

Environmentally Sensitive Approaches with Technology and Engineering Solutions

Technology and engineering knowledge have an important role in finding innovative and permanent solutions to environmental problems. In addition, by supporting the development of problem solving and design-oriented thinking skills, it makes it easier for individuals to make decisions in accordance with sustainability principles in the future (English, 2016; Kelley& Knowles, 2016). In this context, STEM programs include different engineering-based and technological applications that support environmental sustainability. Below is a summary of the key areas of these applications:

Green Technologies: STEM-based education makes it easier for students to gain an idea about energy-saving systems, renewable energy sources and environmentally friendly technologies. Solar energy panels, biofuel production, wind turbines and electric vehicles are prominent examples of this field. These mentioned technologies not only provide structures that enable alternative energy production, but also make significant contributions to environmental sustainability by reducing carbon emissions (Panwar et al., 2011; Bărbulescu et al., 2025).

Sustainable Design: Sustainable design in engineering aims to minimize damage to the environment while also using resources more efficiently. In this process, it is important to prefer environmentally friendly alternatives in the material selection of products and to adopt the circular economy approach (Han et al., 2022). In this way, students get into the habit of evaluating an engineering product not only in terms of its technical function but also in terms of its environmental impact. These skills support individuals in making more conscious choices in areas such as sustainable production or building design in their future lives (Mulder et al., 2012).

Environmental Monitoring and Control Systems: Today, it's possible to collect and transfer environmental information faster, more effectively, and more easily. Certain applications, such as remote sensing techniques, sensor-based tools, and geographic information systems, can facilitate multi-dimensional environmental monitoring projects, such as air pollution, water quality, climate change, and natural disaster risk. By using these systems, students are able to demonstrate a highly sophisticated approach to environmental awareness (Savage et al., 2008; Hayat et al., 2019).

Waste Management and Recycling: Waste management and recycling is vital for the protection of our environment. In this context, STEM education focuses on promoting the new promising solutions that can be developed. It would also benefit the conservation of natural resources and alleviate environmental damages by implementing composting approaches and evolving recycling strategies that can achieve reversible synthesis of biodegradable materials (Kök, 2021).

Creative STEM-Based Solutions to Ecological Problems

STEM education helps students develop original and realistic solutions for the environmental challenges that will occur throughout their lives. In this practice, skills (design thinking, problem solving and creativity) are utilized simultaneously (Beers, 2011; Hilton & Honey, 2011). Shamuganathan (2023) suggests that through nature-inspired approaches like biomimicry, natural systems can be studied and solutions developed. Smart city technologies, for instance, are utilized to create and/or sustain energy, transportation, water management and waste management systems (Akarsu et al., 2020). Additionally, water management techniques such as rainwater catchment and purification save water consumption sustainably (Yaşar-Ekici et al., 2018). Such apps enable students to develop environment-friendly technology and social consciousness.

Examples of Educational Applications and Project-Based Learning

Sustainability Themed STEM Projects

Project-based learning supports students in gaining practical experiences by bringing together their knowledge and skills in different fields (Krajcik & Shin, 2014). STEM based projects not only provided them with the appropriate knowledge but also the opportunity to practice cooperation study, creative thinking, problem solving and critical thinking (Capraro et al., 2013). These sustainability projects provide students with the opportunity to implement innovative, creative solutions to environmental issues. In addition, they support the intellectual aspect of the student and also fosters social awareness (English, 2016). Hence it is easy to see why the project-based STEM initiatives stand out as a viable pathway for students to keep connected with their personal and social growth.

Globally, project-based learning has a strong currency in sustainability education. This method creates active participation of the students and produces diverse classes that are learner-centered (Cörvers et al., 2016; Kricsfalusy et al., 2018). For instance, the students could investigate energy usage of school buildings and create energy conservation methods for them (Aşık et al., 2017). Students can design use strategies on reduceable and recyclable waste (Çoruhlu & Nas, 2018) and carry out projects in the fields of biology with hydroponic systems for the projects to combine agricultural urbanism (Cummings & Cummings, 2021) on engineering and chemistry applied areas.

The Maker Movement and Environmental Approaches

The Maker movement is a method that helps students participate actively in their own production process and therefore learn. This initiative, which links STEM education and sustainability, empowers students to devise solutions to environmental issues and increases awareness of sustainability. One such initiative is known as Maker's Asylum, which has shown tens of thousands of individuals the ropes of hardware design, digital manufacturing and sustainability in India. These kind of projects not only provide a context for sensitivity of students towards environment but also for solution-oriented thinking (Saari et al., 2021) with four main applications, this is a summary of to understand the impact of the maker movement in the domaine of the sustainability. They are: 3D printing and sustainable materials, electronic waste recycling, open-source design and local manufacturing.

3D Printing and Sustainable Materials

In the maker spaces, students use 3D printing for prototyping with environment-friendly material. Innovative 3D products that have less ecological impact are made with bio-degradable polymers and recycled filaments than te conventional plastic (Agrawal Bhat, 2025). Additionally, recycling the waste plastics including high density polyethylene (HDPE) to fabricate filaments may also save energy and facilitate transformation of plastic product model towards circular economies scenarios (Oyinlola et al., 2023). They expose students to sustainable production processes and to sustainable extraction of local inputs.

Electronic Waste Recycling

Maker spaces integrate environmental awareness and ingenuity by repurposing components sourced from discarded electronic equipment. As an example, e-waste toolkit enables access for fabrics with e-waste materials, particularly in low- resource or marginalised areas to enable participants to discover socially-oriented designs alongside individual designs (Vyas et al., 2023). These practices do not only contribute to the creative problem-solving of students, but also the systematic and innovative alternatives within the scope of solid waste management.

Open Source Designs and Local Production

The maker movement promotes the sharing and dissemination of innovations and ideologies based on open source principles. This thereby promotes nearer-to-consumer production and shorter supply chains. For instance, RepRapable Recyclebot is an open-source filament extruder that reprocesses recycled plastic into filament, which not only reduces carbon emissions of long-distance transport of manufacturing fleet but also considerably saves manufacturing cost (Woern et al., 2018).

Interdisciplinary Approaches and Nature-Based Learning in STEM Education

Integrated Use of Science, Mathematics, Engineering and Technology

A key principle of education based on the STEM is an interdisciplinary approach where students can apply knowledge from different disciplines in a connected and systems/holistic way (Holmlund et al., 2018). It is an instructional approach where the teaching and learning of science, technology, engineering and mathematics are integrated in such a way that the contribution of each subject area is interrelated and students have more comprehensive learning experience. As an illustration, in one of the solar energy projects, the students would integrate different physical concepts to electronic circuits and develop engineering solutions for system effectiveness, using the mathematical tools to perform the calculations (Han et al., 2022).

Cross-curricular work may also help students connect the dots on challenging problems, for example when it comes to specific environmental problems like climate change and waste management. Addressing such issues necessitates the interdisciplinary transfer of science, technology, engineering and mathematics (Akarsu et al., 2020; Nugraha et al., 2024). Systems thinking, design-based approaches, and sustainability are all commonly used concepts that can help to bridge knowledge across disciplines and produce an effective solution to a problem as it encourages teamwork (Roehrig et al., 2021; Wu et al., 2024). Hence, It is not merely a vehicle for transferring knowledge between disciplines, but also contributes greatly to skills such as analytic thinking, creativity, and application. Projects that are real-life and holistic design lead to greater success in learning in STEM areas (Holmlund et al., 2018; Akarsu et al., 2020; Roehrig et al., 2021; Han et al., 2022; Nugraha et al., 2024; Wu et al., 2024).

Learning with Nature: Outdoor Laboratories

Nature-based learning embodies the connection between STEM education and ecological sustainability, and it promotes engaging and direct methods of learning from and with nature (Christie et al., 2015). Biodiversity observations, water and air quality measurements in local ecosystems, or investigations of local effects of climate change help students personally experience environmental problems (Toran, 2016; Yaşar-Ekici et al., 2018); while greenhouse systems built in the garden of the school allow students to recognize sustainable agriculture and observe it (Gulhan, 2023; Kanosvamhira, 2025), solar panels and small-scale wind turbines give students a good idea of energy production processes and technology (Cole, 2023). Direct exposure relating to actual practice of scientific process skills empowers learners in the analysis of data, enhances their confidence in data collection and interpretation, leading them to a more informed perspective on environmental issues.

System Thinking Skills and Ecological Awareness

Systems thinking is a holistic way of thinking that makes the study of environmental education issues complex. This mode of thinking recognises the wider system in which a problem is embedded and the interconnections between the elements that constitute this system, instead of analysing the problem in isolation (Arnold & Wade, 2015). Given that many environmental problems are complex, systems-oriented problems with both social and ecological components, fostering a systems perspective can be beneficial to attain solutions in these realms (Williams et al. 2017). Taking a system approach, seen as an integral part of environmental education, may help students to appreciate the relationships among human behaviour and nature. This capacity enables them to design deep rather than shallow responses to wicked environmental problems (Stave & Hopper 2007). It is even greater when considered as an instrument for understanding causes, and also the potential effects of global environmental problems which are more comprehensively defined as climatic changes, loss of biodiversity and natural resources depletion, therefore it demonstrates how the system thinking approach in which scientific thinking is being revealed, so this consciousness acquired with assistance of scientific thinking approach in environment issues help pupils learn how to use this treasure chest information not only for solving such problematic issues that were associated with environment but regularly in their daily lives (Elmas et al., 2021).

The function of ecosystems provides a quick feedback system and it is good for simplifying the training system thinking on the part of student body. It is through a study of interactions that students will be able to evaluate the effect humans have on these systems at an even greater level whilst considering how all living and nonliving things are interrelated to each other. Such an outlook allows students to reach beyond contemporary consequences of global problems and find a future direction for their lives. Since the concept of cycles and processes like carbon and water cycle have the potential of being inspiring metaphor for students, they can understand the relationship among natural system (Soderquist & Overakker, 2010; Tidball & Krasny, 2011).

For instance, environmental problems affect them in local to global scales, so multi-scale thinking help learners to understand these complex relations (Bi et al., 2021). This skill encourage students to consider the local and global impact processes and understand sustainable processes on the environment (Milfont et al., 2012). They turn into analysts; but more importantly, they create more sustainable, more creative solutions to these complex environmental problems. The students also learn to integrate their science, engineering and math knowledge to implement their solutions to the environmental problems presented (Semerjian et al., 2004).

Discussion

There is a special relationship between environmental sustainability and STEM education in contemporary education. STEM integrates science, technology, engineering and mathematics in order to engage students in developing such skills as critical thinking, problem solving and creativity. Environmental-sustainability education also teaches students to be aware of their environment. Literature stated that integrating these two disciplines will create learning environment to enhance the students' academic and competencies as well as raising their environmental sensitivity (Enön & Hiğde, 2024; Cordaro et al., 2025). It is proven from a research that the integrated teaching of STEM education and environmental sustainability contributes to the improvement of students' academic performance as well as their ecological knowledge (Han et al., 2022). This combination of subjects assists in solving scientific and creative problems around the daily life problems the student experiences, and even develops their critical thinking, problem solving and systematic view. Moreover, environmental-centered STEM studies support individuals to gain positive attitudes related to environment and gain habits of sustainability (Ayverdi et al., 2024).

The Maker approach, blending together STEM education and sustainability and merging the do-it-yourself concept with technology, is one of the vital approaches (Sönmez & Şahinkayası, 2021). This approach allows students to come up with creative and innovative solutions while also applying their theoretical knowledge. Real-world problem-solving engages students to learn, and likely remember more of what they have learned. On the contrary, Maker spaces allow students' enhancement of skills related to technology and play a role for sustainable technologies (Demir & Güneş, 2020).

The education of STEM encourages and supports the creation of new initiatives to address environmental concerns. The use of science, interdisciplinary projects, and technology allows students to discover and analyze real-world environmental problems to brainstorm creative, tech-based solutions. Nonetheless, they have not been without their shortcomings, including an inadequate treatment of the social and cultural dimensions, a limited examination of the economic and political context, and a general neglect of local knowledge and traditional practices. Therefore, it is seen necessary to address the integration of STEM education and environmental sustainability with a more comprehensive and balanced approach (Uslu ve Boz-Yaman, 2021).

Conclusion

The connection between STEM education and environmental sustainability not only supports the academic development of students but also paves the way for positive changes in society. The STEM approach aims to provide students with skills in scientific thinking, engineering design and technology use (Beers, 2011; Hilton & Honey, 2011), while increasing environmental awareness through sustainability education. The integration of these two fields helps students learn and also makes them recognize their responsibility towards the environment. Hence better-prepared citizens are prepared for the challenges of this new and challenging times (Bybee, 2010).

STEM education has been shown to be effective and the interdisciplinary nature of STEM education creates opportunity for students to be exposed to a more complex and broad perspective on environmental issues. Students learn about environmental issues which will prepare them to act more sustainably with the help of STEM sustainability projects (Christie et al., 2015). Apart from that, these projects helps in building our critical thinking, creativity and communication skill as well as collaborating with others. It further promotes the growth of 21st century skills (Han et al., 2022). STEM-Sustainability integration is an education to serve both individual development and the good of society in a holistic way.

Since the STEM education as well as the sustainability theme provides the possibility of assessing the information of various disciplines together, it is not hard to see the connections between disciplines more clearly by students (Akarsu et al., 2020) The coupling of STEM, the sustainability topic enables the assessment of varied information from different disciplines together, and it also helps students to realize the connections between those disciplines more easily. Particularly when used with project-based learning, sustainability-driven projects allow for greater student engagement in the learning process — a win-win for students and educators! Such projects provide opportunities for students to not only gain knowledge, but also acquire experience as they apply this knowledge into real-life environmental issues (Lee & Lee, 2025). Providing enhanced learning with environmental material allows students to develop a closer relationship with their environment, potentially creating a tangible link between school and real-life experiences (Savage et al., 2008).

The future of STEM education and sustainability will continue to evolve in the next few years due to technology, education trends, and changes in our society. Considering the widespread models of data, the prevalence of digital technologies, such as artificial intelligence, the internet of things and big data analysis, digital tools may facilitate greater integration and larger-scale consumption of this integration (Bărbulescu et al., 2025). In addition, the pertinacity of the climate crisis and environmental degradation illustrates the urgent need for education systems to transform towards sustainability. Integrating STEM education with sustainability is capable of supporting not only the academic and intellectual development of individuals, but also the achievement of long-term environmental goals by societies (Li, 2025).

Recommendations

In order to integrate STEM education and sustainability issues more effectively, it is necessary to review the national and local curricula. In this context, a structure that supports interdisciplinary perspectives and allows students to connect with real-life problems should be highlighted (Bybee, 2010; Beers, 2011; Akgündüz et al., 2015). In order for this transformation at the curriculum level to be effective, it is also important to support teachers pedagogically and to provide the infrastructure needed in practice (Altunel, 2018; Yaşar-Ekici et al., 2018). In addition, restructuring the evaluation systems in accordance with this change and re-structuring them with project-based, practice-based and process-oriented methods can be a strong step that will strengthen both the academic development of students and their environmental awareness (Toran, 2016; Bascopé ve Reiss, 2021).

Effective transfer of STEM education and sustainability to the classroom environment is possible when teachers continuously improve their knowledge and skills in these areas (Hilton & Honey, 2011). Teachers who regularly participate in professional development activities can apply both current pedagogical approaches and technology integration more effectively. Teachers from different disciplines working together on projects supports students to experience a multidimensional and holistic learning process (Yıldız et al., 2021). In this context, integrating educational technologies into the teaching process in the right way also contributes to the development of students' digital literacy skills (Christie et al., 2015). Including local environmental issues in course content places an important responsibility on teachers to increase students' environmental awareness (Huang, 2024). All these elements, together with the strengthening of teachers' professional competencies, make it possible to successfully implement an interdisciplinary and sustainability-focused STEM practice at the classroom level (Rehman et al., 2025).

Merely incorporating STEM education and sustainability into course content is insufficient; it is crucial to infuse this approach throughout the school's operations and culture. Schools that collaborate with local communities, universities, and industry offer richer learning experiences for both students and educators (Holmlund et al., 2018). School campuses serve as dynamic learning environments where students can bridge theory and practice in sustainability. By actively participating in project planning, implementation, and evaluation, students engage in participatory learning and develop a sense of responsibility (Christie et al., 2015; Han et al., 2022). Holistic approaches not only enhance academic growth but also cultivate students' awareness of environmental issues and long-term responsibility. This nurtures individuals who can contribute to building a sustainable future (Barth & Rieckmann, 2012).

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Chapter 10

Expanding STEAM through Heritage and Social Sciences: A Framework for Innovation and Cultural Sustainability

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Chapter Highlights

This chapter highlights a culturally grounded and interdisciplinary STEAM+S framework that integrates heritage, theory, and practice to foster meaningful, future-oriented learning experiences.

- Heritage-Based STEAM+S Framework – Expands traditional STEAM by integrating the social sciences, positioning heritage, culture, and identity as core dimensions of interdisciplinary learning.
- Theoretical Foundations – Grounds the framework in constructivist and sociocultural theory, enriched by design thinking and creative thinking, to support authentic, learner-centred, and culturally meaningful learning experiences.
- Cultural Contextualization through Defensive Architecture – Utilizes Omani forts, castles, and towers as culturally rich contexts, transforming abstract disciplinary knowledge into real-world, meaningful applications.
- Interdisciplinary Integration – Connects science, technology, engineering, arts, mathematics, and social sciences to promote higher-order thinking, problem-solving, innovation, and creativity.
- Educational and Pedagogical Implications – Provides a roadmap for curriculum design through project-based and inquiry-driven learning, while redefining the teacher's role as a facilitator, mentor, and co-learner.

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Introduction

The rapid pace of scientific advances, technological innovations, and knowledge breakthroughs has created new challenges that demand innovative solutions. Education must, therefore, prepare learners with the competencies and skills that are essential for the twenty-first century, moving beyond rote memorization toward authentic, applied learning. In this context, STEAM education has emerged as a powerful interdisciplinary approach for cultivating creativity, critical thinking, problem-solving, and innovation (Perignat & Katz, 2019; Siekmann & Korbel, 2016).

Internationally, STEAM has gained recognition for its role in addressing global economic and technological needs. It emphasizes not only strengthening teachers' capacity to teach across disciplines but also motivating students to pursue STEAM-related fields (Bureau of International Education, 2015). Defined as the integration of science, technology, engineering, arts, and mathematics, STEAM connects academic content with real-world contexts in ways that foster discovery and deeper understanding (Perignat & Katz, 2019). Scholars further describe STEAM as an umbrella framework that bridges disciplinary knowledge with societal productivity, identity, and community life (Mengmeng et al., 2019; Shahat & Al-Balushi, 2023).

The theoretical foundations of STEAM are rooted in constructivist and sociocultural perspectives, which emphasize the importance of authentic tasks, collaboration, and cultural context in knowledge construction (Fosnot, 2013; Vygotsky, 1978; Mengmeng et al., 2019). Research confirms that STEAM enhances achievement in science, mathematics, technology, and the arts while also nurturing life skills, ecological literacy, and motivation for lifelong learning (Beghetto & Kaufman, 2014; Pertiwi et al., 2024). Within this paradigm, the teacher's role shifts from being a transmitter of knowledge to a facilitator of inquiry and collaboration (Al-Balushi et al., 2022, 2025b; Ambusaidi et al., 2022).

Building on this foundation, the present study proposes a heritage-based extension of STEAM (STEAM+S) that incorporates the social sciences as a central dimension. Specifically, it situates defensive architecture–including castles, forts, and walls–as a culturally authentic context through which learners can engage with science, mathematics, technology, engineering, and the arts, while also exploring history, sociology, and identity. Heritage architecture serves not only as a record of societal practices but also as a reservoir of scientific, artistic, and technological knowledge shaped by environmental, political, and cultural factors (Al-Maamari, 2020, 2022).

Within this framework, design thinking is employed as a structured, iterative process that fosters problem-solving, innovation, and collaboration (Nagai & Noguchi, 2003; Razzouk & Shute, 2012; Simon, 1996). Complementing it, creative thinking equips learners with the fluency, flexibility, originality, and elaboration needed to generate meaningful solutions (Beghetto & Kaufman, 2014; Guilford, 1967; Torrance, 1974). Together, these two thinking paradigms transform heritage-based learning into a dynamic platform for cultivating twenty-first-century skills.

Accordingly, this chapter situates STEAM education within a heritage-based, interdisciplinary model that highlights defensive architecture as an entry point for integrating the sciences, arts, mathematics, and social sciences. By doing so, it underscores how STEAM+S, design thinking, and creative thinking can converge to equip learners with innovative, future-oriented skills while simultaneously strengthening cultural identity and societal sustainability (Al-Hushani, 2019; Oman Vision 2040, 2019).

Rationale of this study

The Sultanate of Oman is distinguished by its rich heritage of defensive architecture, including castles, forts, towers, and protective walls. Recognizing their cultural and historical significance, the Ministry of Heritage and Culture has invested in the restoration of major sites through systematic scientific processes that combine documentation, archaeological excavation, traditional restoration methods, regular maintenance, and carefully planned modern adaptations carried out in ways that preserve architectural authenticity. These structures–some dating back more than three millennia–serve not only as monuments of the past but also as enduring symbols of Oman's distinct urban identity in the face of contemporary economic, social, and cultural transformations (Al-Hushani, 2019; Oman Vision 2040, 2019).

The educational value of defensive architecture lies in its potential to cultivate diverse forms of thinking. By analysing how these structures reflect environmental adaptation, engineering ingenuity, artistic expression, and cultural values, students can engage in authentic learning experiences that foster critical, creative, and design thinking. Such learning aligns with Oman's national educational goals, which emphasize inquiry, reflection, cultural awareness, and problem-solving, as well as with Oman Vision 2040, which prioritizes the development of future skills within a globally competitive, yet culturally grounded, workforce (Al-Balushi et al., 2022; Ambusaidi et al., 2022).

In today's knowledge society, education must move beyond the transmission of facts to equip learners with the skills, independence, and adaptability needed to navigate twenty-first-century challenges (Fosnot, 2013; Vygotsky, 1978). Scholars have underscored the importance of nurturing creative and design thinking as foundational capacities for innovation and resilience (Beghetto & Kaufman, 2014; Guilford, 1967; Nagai & Noguchi, 2003; Razzouk & Shute, 2012; Torrance, 1974). Parallel research has also highlighted the value of STEAM integration in linking disciplines, developing life skills, and fostering both ecological literacy and innovation (Perignat & Katz, 2019; Mengmeng et al., 2019; Shahat & Al-Balushi, 2023).

Against this backdrop, the present study introduces a heritage-based STEAM+S framework, where the "S" represents the social sciences. By utilizing defensive architecture as the entry point for interdisciplinary learning, the study aims to demonstrate how cultural identity and modern educational needs can converge to foster design and creative thinking skills essential for preparing Omani learners for the future, while also offering a model with global applicability.

Literature Review and Theoretical Framework

Global Perspectives on STEAM Education

Global literature demonstrates that STEAM has emerged as a powerful interdisciplinary model designed to equip learners with the competencies and dispositions required in the twenty-first century. By integrating science, technology, engineering, arts, and mathematics into a cohesive framework, STEAM promotes creativity, critical thinking, and problem-solving–skills that are increasingly demanded in contemporary societies (Perignat & Katz, 2019; Siekmann & Korbel, 2016). International organizations have emphasized the importance of STEAM in preparing students for innovation-driven economies while enhancing teachers' pedagogical capacities for interdisciplinary instruction (Bureau of International Education, 2015).

Empirical studies across contexts provide evidence of STEAM's effectiveness in developing both cognitive and affective outcomes. For example, research confirms that STEAM-based instruction enhances students' critical thinking, creativity, and motivation across multiple disciplines and grade levels (Beghetto & Kaufman, 2014; Pertiwi et al., 2024). Similarly, Mengmeng et al. (2019) emphasize the importance of sociocultural approaches to STEAM, which embed learning in authentic, collaborative contexts. These findings underscore the adaptability of STEAM across various educational stages and disciplines, affirming its potential to enhance higher-order thinking and learner engagement.

Despite these promising outcomes, the review reveals that most studies focus heavily on the applied sciences and mathematics, with limited attention to identity-related domains such as heritage and culture. This represents a notable gap in the global discourse. Current implementations often overlook the historical and cultural dimensions that have long shaped scientific and technological achievements. For instance, the Egyptian pyramids were not only feats of engineering, mathematics, and artistry but also expressions of cultural and religious values. Similarly, The Great Wall of China reflects both engineering ingenuity and sociopolitical imperatives, while Islamic fortified castles demonstrate the integration of environmental adaptation, architecture, and societal needs.

Building on this insight, the present study proposes an extended model–STEAM+S (Social Sciences/Heritage)–to bridge the applied sciences with cultural and identity-oriented dimensions. The model recognizes that history and culture are not peripheral but rather central forces shaping how science, technology, engineering, arts, and mathematics are conceived, developed, and applied. By integrating heritage and identity into STEAM education, learners experience an enriched interdisciplinary approach that connects them to their cultural context while also developing design thinking and creative problem-solving capacities (Razzouk & Shute, 2012; Nagai & Noguchi, 2003; Torrance, 1974).

This perspective is particularly relevant in Oman, where defensive architecture such as forts, castles, and towers stands as a living testament to the intersection of technological ingenuity, environmental adaptation, and cultural identity (Al-Balushi et al., 2022; Ambusaidi et al., 2022). By situating STEAM education within this heritage-based framework, the study not only addresses the underexplored intersection of STEAM and the social sciences but also contributes to the national priorities of Oman Vision 2040 – strengthening identity and citizenship while preparing learners with the future-ready skills needed in a globally competitive society (Oman Vision 2040, 2019).

Integration of Social Sciences in STEAM

While the global literature has widely emphasized the integration of science, technology, engineering, arts, and mathematics, comparatively little attention has been devoted to incorporating the social sciences as an explicit dimension of STEAM. Yet, education is not solely a technical endeavour; it is also inherently cultural, historical, and societal. By excluding heritage, history, and social studies, conventional STEAM approaches risk overlooking the broader contexts that both shape and give meaning to scientific and technological advancements.

Recent scholarship highlights the importance of incorporating sociocultural dimensions into STEAM pedagogy. Perignat and Katz (2019) argue that true interdisciplinarity necessitates moving beyond disciplinary silos to incorporate real-world contexts, particularly those grounded in culture and community. Similarly, Siekmann and Korbel (2016) highlight that STEAM has evolved as an umbrella framework–one that should encompass not only technical learning but also initiatives related to citizenship, national productivity, and social responsibility. These insights provide a theoretical basis for extending STEAM to include the social sciences as a sixth dimension, thereby broadening its scope and relevance.

The case for such integration becomes especially evident when examining historical achievements. Monumental structures such as the Egyptian pyramids, the Hanging Gardens of Babylon, and the Great Wall of China demonstrate how social, political, religious, and cultural motivations directly influenced scientific, mathematical, and engineering innovations. In the Omani context, defensive architecture including forts, castles, and towers embodies not only technological ingenuity but also cultural identity, spiritual values, and community resilience (Al-Balushi et al., 2022; Ambusaidi et al., 2022). These examples illustrate that science and engineering cannot be meaningfully separated from their cultural and societal drivers.

Positioning heritage and history as integral dimensions within STEAM– what this study refers to as STEAM+S offers a richer and more holistic model of education. The framework situates learning at the intersection of disciplinary knowledge and socio-cultural identity, allowing learners to engage with authentic contexts that develop both technical competencies and civic understanding. In practice, this enables students to acquire twenty-first-century skills, such as critical thinking, design thinking, and creativity, while simultaneously fostering an appreciation of heritage, cultural identity, and civic responsibility (Razzouk & Shute, 2012; Nagai & Noguchi, 2003).

In Oman, this integration aligns closely with the national priorities outlined in Oman Vision 2040, which emphasize strengthening identity, citizenship, and cultural sustainability alongside innovation and global competitiveness (Oman Vision 2040, 2019). Thus, the STEAM+S framework provides dual benefits: it enhances learners' problem-solving and creative capacities while embedding these competencies within a culturally grounded, socially responsive model. This positions STEAM+S not only as an educational innovation but also as a strategic response to national development goals and a contribution to the global discourse on interdisciplinary, heritage-based education.

Heritage and Education

Cultural heritage represents a vital dimension of education, serving not only as a record of human achievement but also as a foundation for developing learners' sense of identity, belonging, and citizenship. Heritage encompasses both tangible elements, such as architecture, monuments, and artifacts, and intangible aspects, including traditions, values, and collective memory. From an educational perspective, heritage provides authentic, real-world entry points that connect students to their cultural heritage while also fostering essential twenty-first-century skills. This vision aligns with Omani educational priorities, which emphasize preparing learners for innovation-driven societies while maintaining cultural sustainability (Al-Hushani, 2019; Al-Balushi et al., 2022; Ambusaidi et al., 2022). At the theoretical level, constructivist and sociocultural perspectives reinforce the value of heritage contexts, highlighting that authentic, situated experiences play a central role in shaping meaningful learning (Fosnot, 2013; Vygotsky, 1978).

Globally, heritage education has been recognized as a powerful means of cultivating civic identity and global citizenship. UNESCO (2018) emphasizes that engaging learners in the exploration of historical sites, cultural practices, and intangible traditions equips them not only with factual knowledge but also with the ability to critically reflect on the relationships between the past and the present. This pedagogical approach enables education to move beyond the transmission of abstract knowledge, anchoring learning in contexts that are meaningful, situated, and socially relevant.

In the Omani context, defensive architecture including forts, castles, and towers constitutes a distinctive dimension of the nation's cultural heritage. These structures are not merely military relics If you'd like to maintain a parallel structure, change to: "but also embody of accumulated expertise in engineering, construction, environmental adaptation, and artistic expression, while also reflecting broader social, political, and religious realities (Al-Balushi et al., 2022; Ambusaidi et al., 2022). For example, the design of thick fortress walls demonstrates mathematical precision and adaptation to climatic conditions, while intricate decorative motifs carved into doors and ceilings reflect the aesthetic values and cultural identity of the communities that built them. As such, defensive architecture offers a multidisciplinary resource that integrates science, technology, engineering, arts, mathematics, and social sciences.

The educational potential of heritage-based contexts lies in their ability to foster both cognitive and affective outcomes. Cognitively, they challenge learners to analyse structures, interpret their functions, and connect them with scientific and mathematical principles. Affectively, they strengthen cultural pride, identity, and a sense of continuity with the past. This dual capacity aligns with contemporary calls for education that balances skill development with identity formation, a need made increasingly urgent by the forces of globalization (Perignat & Katz, 2019; Mengmeng et al., 2019).

While prior STEAM research has largely focused on applied sciences and mathematics, the integration of heritage and identity remains underexplored. By positioning defensive architecture as the entry point for the proposed STEAM+S framework, this study advances a new direction in educational research and practice one that embeds design and creative thinking within culturally authentic contexts. Such an approach ensures that learners not only acquire transferable twenty-first century skills but also deepen their appreciation of heritage, in line with Oman Vision 2040's emphasis on identity, citizenship, and cultural sustainability (Oman Vision 2040, 2019).

Theoretical Framework: The STEAM + S Model

Constructivist Learning Theory

Constructivist learning theory posits that learners actively construct their own knowledge by engaging with authentic, meaningful tasks rather than passively receiving information. Learning occurs when individuals interact with real-world contexts that challenge prior conceptions, prompting them to reorganize and extend their understanding (Piaget, 1972; Fosnot, 2013). In this paradigm, the role of the teacher shifts from being a transmitter of knowledge to a designer of learning environments that stimulate inquiry, exploration, and reflection (Shahat & Al Amri, 2023).

Within the STEAM+S framework, constructivism provides the foundational lens for connecting disciplinary knowledge with cultural and social realities. Defensive architecture-such as Omani forts, castles, and towers functions as a real-world context that unites science, technology, engineering, arts, mathematics, and social sciences. For example, when investigating the structural design of a fort, learners may calculate wall thicknesses to explore geometry, apply engineering principles to test stability, analyse materials for climate adaptation, study decorative arts for cultural symbolism, and reflect on the historical and social motivations behind architectural choices (Ambusaidi et al., 2022; Al-Balushi et al., 2022).

This approach shifts learning from abstract concepts to practical applications. Instead of viewing geometry as a set of isolated formulas, students engage in tasks such as measuring arches or simulating construction methods to understand the concept of structural stability. Rather than treating history as a sequence of memorized dates, learners analyse how political, social, and religious forces influenced design decisions. Through these activities, students actively construct meaning, linking disciplinary knowledge to lived experiences and cultural identity (Perignat & Katz, 2019; Vygotsky, 1978).

In the Omani context, where defensive architecture symbolizes resilience, ingenuity, and cultural continuity, the constructivist application of STEAM+S enables learners to achieve both cognitive outcomes (problem-solving, design thinking, creative thinking) and affective outcomes (identity formation, cultural pride, and social responsibility). Projects such as building scale models of forts, conducting digital simulations, or analysing restoration practices not only enhance interdisciplinary knowledge but also highlight the relevance of this knowledge to learners' own society and heritage (Shahat & Al-Balushi, 2023; Ambusaidi et al., 2022).

Thus, constructivist learning theory validates the use of heritage-based defensive architecture as a pedagogical tool within the STEAM+S model, positioning learners as active participants in knowledge construction while grounding their learning in culturally authentic contexts that bridge the global and the local (Oman Vision 2040, 2019).

Sociocultural Theory

Sociocultural theory, grounded in the work of Vygotsky (1978), emphasizes that learning is inherently social and shaped by cultural and historical contexts. Knowledge is constructed through interaction with others, mediated by language, tools, and shared cultural practices. Central to this perspective is the zone of proximal development (ZPD), which illustrates how learners can achieve higher levels of understanding through guided support, collaboration, and social interaction.

Within the STEAM+S framework, sociocultural theory reinforces the view that education is not only cognitive but also cultural and contextual. Defensive architecture, a distinct feature of Omani heritage, serves as a cultural tool that facilitates learning. When students engage with forts, castles, or towers, they are not simply examining physical structures- they are interacting with artifacts that embody the collective history, values, and social identity of their communities (Al-Balushi et al., 2022; Ambusaidi et al., 2022). This engagement situates learning within meaningful cultural contexts, bridging the past and present while preparing students for future societal roles.

Collaborative learning activities- such as group projects to design scale models of heritage buildings, role-playing debates about their historical significance, or community-based restoration initiatives– illustrate the sociocultural dimension of STEAM+S. Through these tasks, learners co-construct knowledge, negotiate meaning, and develop shared understandings that integrate scientific inquiry with social and cultural awareness (Mengmeng, Li, & Chen, 2019; Perignat & Katz, 2019). Teachers, in turn, act as facilitators and mediators, scaffolding learning by connecting disciplinary concepts to cultural narratives and lived experiences (Shahat & Al Amri, 2023).

The integration of the social sciences as a sixth dimension ensures that STEAM education extends beyond technical mastery to cultivate identity, citizenship, and cultural continuity. In alignment with Oman Vision 2040 (2019), sociocultural theory provides the theoretical justification for embedding heritage into interdisciplinary learning. It validates the idea that students' intellectual growth is inseparable from their social environments, traditions, and community practices.

Thus, sociocultural theory strengthens the STEAM+S framework by positioning heritage-based defensive architecture not merely as content, but as a mediational tool-a bridge between learners' cultural identity and their acquisition of twenty-first-century skills.

Design Thinking Framework

Design thinking is an iterative human-centred process that emphasizes creativity, problem-solving, and innovation. Rooted in the practices of designers and engineers, it has been widely adapted into education as a framework to help learners approach complex challenges with empathy, experimentation, and reflection (Razzouk & Shute, 2012; Nagai & Noguchi, 2003). The process typically unfolds through cyclical stages empathize, define, ideate, prototype, and test each of which encourages learners to generate, refine, and evaluate solutions collaboratively (Simon, 1996).

Within the STEAM+S model, design thinking serves as the methodological engine that enables students to engage actively with heritage-based contexts, such as Omani defensive architecture. For instance, when learners investigate how a fort was designed to balance structural stability, environmental adaptation, and defence against threats, they begin by empathizing with the needs of past communities. They then define the architectural problem, ideate possible solutions, and prototype models using modern materials or digital simulations before testing and refining their designs. This cyclical process mirrors the historical challenges faced by architects while simultaneously fostering twenty-first century competencies (Shahat & Al Amri, 2023).

Design thinking also bridges the technical and cultural dimensions of STEAM+S. By integrating engineering principles with artistic creativity and social understanding, students learn to balance function and aesthetics, utility and symbolism. For example, a classroom project might ask learners to redesign a fort's gate to be both structurally secure and reflective of Omani cultural motifs. Such a task bridges the connection between mathematics and engineering, on the one hand, and art and heritage, on the other, positioning design as a site where culture and innovation converge (Perignat & Katz, 2019).

Moreover, design thinking aligns closely with constructivist and sociocultural theories by positioning learners as active creators of knowledge in authentic, collaborative contexts. It fosters both divergent and convergent thinking, enabling students to explore multiple possibilities before narrowing them down to feasible solutions. Importantly, design thinking cultivates resilience, as learners come to view setbacks and failures as opportunities for iteration and growth rather than as endpoints (Beghetto & Kaufman, 2014).

In the Omani context, embedding design thinking into STEAM+S not only enhances problem-solving and innovation but also strengthens learners' sense of cultural continuity. By reimagining heritage architecture through design challenges, students develop both technical competence and cultural literacy embodying the dual goals of Oman Vision 2040 (2019): global competitiveness and cultural sustainability.

Thus, the design thinking framework operationalizes STEAM+S, transforming heritage-based learning into a dynamic process of inquiry, innovation, and cultural engagement.

Creative Thinking Framework

Creative thinking is widely recognized as one of the essential competencies of the twenty-first century, enabling learners to generate novel, valuable, and contextually relevant solutions to complex problems (Beghetto & Kaufman, 2014; Perignat & Katz, 2019). Foundational work by Guilford (1967) and Torrance (1974) identified its core dimensions as *fluency* (generating many ideas), *flexibility* (shifting perspectives), *originality* (producing unique ideas), and *elaboration* (refining and extending ideas). More recent perspectives extend these dimensions, framing creative thinking as a dynamic process that integrates imagination, critical analysis, and practical application within real-world contexts (Beghetto & Kaufman, 2014).

Within the STEAM+S framework, creative thinking serves as a cognitive driver that transforms disciplinary knowledge into innovative outcomes. Heritage-based contexts such as Omani defensive architecture provide fertile ground for cultivating creativity. For instance, analysing the geometric patterns of castle walls or the artistic carvings on wooden doors allows learners to experiment with combining mathematical precision, engineering functionality, and cultural symbolism. These tasks stimulate divergent thinking while grounding creativity in authentic cultural narratives (Al-Balushi et al., 2022; Ambusaidi, et al., 2022).

Creativity in this model extends beyond the production of new artifacts to include the reinterpretation of heritage. When learners reimagine how forts could be adapted for modern community use while retaining their historical identity, they engage in acts of creativity that bridge tradition and innovation. This duality resonates with Oman Vision 2040 (2019), which emphasizes cultural sustainability while also cultivating future-ready competencies such as problem-solving, innovation, and adaptability.

Moreover, creative thinking complements design thinking within STEAM+S. While design thinking provides structured stages for addressing problems (Razzouk & Shute, 2012; Nagai & Noguchi, 2003), creative thinking enriches each stage with imaginative possibilities and novel perspectives. Together, they foster an educational environment in which learners can move beyond conventional solutions, embrace experimentation, and develop confidence in their ability to contribute new ideas (Beghetto & Kaufman, 2014).

Classroom applications may include brainstorming sessions, creative prototyping, artistic reinterpretations of heritage motifs, and collaborative projects where students generate multiple solutions to shared problems. Through these activities, learners develop not only technical and artistic competencies but also openness, resilience, and aesthetic appreciation qualities that are essential for innovation in a globalized, interconnected world (Shahat & Al-Balushi, 2023).

In sum, the creative thinking framework strengthens STEAM+S by equipping learners to transform interdisciplinary integration into original, socially and culturally meaningful contributions. By linking creativity with heritage, students are encouraged to value their cultural identity while cultivating the imaginative capacities required to navigate and shape the future.

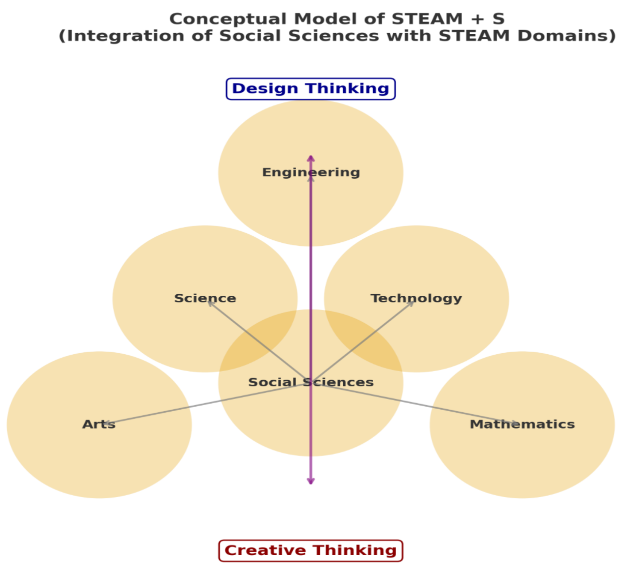

Figure 1. Conceptual Model of STEAM+S

The Heritage-Based STEAM+S Framework

Conceptualization of the Model

The Heritage-Based STEAM+S framework is conceptualized around the principle that cultural heritage particularly defensive architecture can serve as an authentic entry point for interdisciplinary learning. Castles, forts, towers, and protective walls are not only historical landmarks but also living examples of how scientific, technological, engineering, artistic, mathematical, and social dimensions converge to meet societal needs. By situating learning within these culturally grounded contexts, the model enables students to connect abstract disciplinary knowledge to real-world applications that are both meaningful and identity-sustaining (Al-Balushi et al., 2022).

The framework draws on interdisciplinary integration across six domains, highlighting how defensive architecture embodies the full spectrum of STEAM+S:

- Science: Understanding the natural materials used in construction, their geological sources, and how environmental conditions such as climate and erosion influence structural durability (Ambusaidi et al., 2022).
- Technology: Exploring both traditional and modern construction methods, restoration techniques, and innovative approaches to heritage preservation (Al-Hushani, 2019).
- Engineering: Analysing structural design, stability, and defensive functionality, including how architectural forms adapted to terrain, warfare, and community protection (Shahat & Al Amri, 2023).
- Arts: Investigating the aesthetic and symbolic dimensions of architecture, including decorative motifs, calligraphy, woodwork, and designs that reflect cultural identity (Perignat & Katz, 2019).
- Mathematics: Applying geometry, measurement, proportionality, and spatial reasoning in examining architectural layouts, wall thickness, arches, and towers (Guilford, 1967; Torrance, 1974).
- Social Sciences: Examining the historical, cultural, and societal forces that shaped architectural decisions, including security needs, governance structures, religious influence, and community identity (Al-Maamari, 2020, 2022; Oman Vision 2040, 2019).

This conceptualization underscores that defensive architecture is not merely a subject of historical interest but a multidimensional learning resource. Through the STEAM+S framework, learners apply disciplinary knowledge, engage in design and creative thinking (Beghetto & Kaufman, 2014), and strengthen their cultural identity and citizenship awareness by situating learning in authentic Omani heritage. In doing so, the framework aligns with Oman Vision 2040's priorities of sustaining cultural identity while equipping learners with innovation-oriented, globally competitive skills (Oman Vision 2040, 2019).

Application of the Framework

The application of the Heritage-Based STEAM+S framework lies in transforming cultural landmarks into living laboratories for interdisciplinary learning. This approach enables students to bridge theoretical knowledge with hands-on exploration, while simultaneously cultivating cultural identity, design thinking, and creative problem-solving skills (Ambusaidi, et al. 2022, Shahat et al., 2025a). By embedding learning in culturally authentic contexts, the model aligns with both constructivist and sociocultural perspectives, which emphasize the importance of meaningful, situated tasks in building knowledge (Fosnot, 2013; Vygotsky, 1978).

Interdisciplinary Applications

- Science: Students investigate the chemical and physical properties of materials such as stones, clays, and woods, analysing how they contributed to the durability of forts and castles. They also examine environmental adaptations, including insulation and natural ventilation systems that reflect traditional ecological knowledge (Ambusaidi et al., 2022; Aldayri et al., 2023).
- Technology: Learners compare historical construction tools and methods with modern techniques such as 3D scanning and digital modelling, while also studying preservation practices that integrate traditional materials with contemporary technologies (Al-Hushani, 2019; Shahat et al., 2024a,b,c,d). This highlights how heritage preservation embodies the intersection of tradition and innovation.
- Engineering: By analysing wall thickness, arches, and towers, students explore the principles of stability and defensive functionality. Using simulations or prototypes, they test redesign scenarios to enhance resilience while preserving the authenticity of heritage. Such tasks foster engineering design competencies critical to STEM education (Shahat, et al., 2022; Shahat et al., 2024d).
- Arts: Students engage with decorative motifs, carvings, calligraphy, and inscriptions, interpreting their symbolic meanings and cultural significance. They then produce new designs inspired by Omani heritage, demonstrating how artistic creativity and identity are interwoven within architectural contexts (Perignat & Katz, 2019; Beghetto & Kaufman, 2014).
- Mathematics: Learners apply geometry, measurement, proportionality, and spatial reasoning by calculating angles, dimensions, and layouts of forts and castles. Activities include creating scale models or digital simulations, linking abstract mathematical principles to real-world architectural challenges

(Piaget, 1972; Guilford, 1967; Torrance, 1974).

- Social Sciences: Students investigate historical narratives, sociological influences, and cultural values embedded in defensive architecture, situating heritage within broader contexts of security, governance, and community identity (Al-Maamari, 2020, 2022; Oman Vision 2040, 2019). This dimension underscores the social and cultural embeddedness of knowledge, aligning with global perspectives on citizenship and sustainability (Bureau of International Education, 2015; Mengmeng, Li, & Chen, 2019).

Classroom Examples

The application of the Heritage-Based STEAM+S framework in classroom practice can be illustrated through a range of interdisciplinary units that merge disciplinary knowledge with cultural and historical contexts. These examples demonstrate how heritage can function as a living laboratory, supporting both cognitive and affective learning outcomes (Fosnot, 2013; Vygotsky, 1978; Shahat & Al-Balushi, 2023).

The Geometry and Symbolism of Forts

This unit could begin with a site visit (physical or virtual) to a heritage site. Students would measure structures (mathematics), analyse stability and load-bearing principles (engineering), test building materials (science), explore cultural motifs and symbolism (arts), and examine historical accounts (social sciences). The project might culminate in scaled prototypes, 3D-printed reconstructions, or digital simulations, accompanied by student presentations that explicitly connect technical design to cultural meaning. Such tasks foster higher-order thinking and identity formation while situating abstract concepts in real-world contexts (Guilford, 1967; Torrance, 1974; Ambusaidi, Shahat, & Al Musawi, 2022).

Sustainability Lessons from Ancient Water Systems

Students investigate aflaj systems in Oman or Roman aqueducts, examining water flow and chemistry (science), calculating capacity, ratios, and geometry (mathematics), analysing engineering strategies for channelling water across terrain (engineering), and discussing the sociocultural role of these systems in sustaining communities (social sciences). Learners could design modern adaptations using renewable energy or digital monitoring technologies (technology), while producing artistic maps and visualizations of historical water networks (arts). This example highlights the global transferability of STEAM+S and its potential to address contemporary sustainability challenges

(Aldayri et al.,, 2023; Perignat & Katz, 2019).

Mathematics in Islamic Geometric Art

Here, learners analyse tessellations and geometric patterns in fort decorations (mathematics), investigate the tools and techniques used in carving and design (technology), connect motifs to architectural principles of balance and symmetry (engineering), and reflect on their cultural and symbolic significance (social sciences). Students then create their own designs using both traditional tools and digital design software, merging artistic creativity with mathematical precision. This task develops both technical skills and aesthetic appreciation, in line with calls for integrating creativity into STEAM pedagogy (Beghetto & Kaufman, 2014; Shahat & Al-Balushi, 2023).

Defensive Architecture and Community Life

This unit involves students investigating how forts functioned not only as military structures but also as centres of governance, trade, and culture. Learners explore the chemistry and durability of construction materials (science), model fort defences under different scenarios (engineering), recreate market scenes or storytelling traditions linked to forts (arts), and analyse historical records about community life (social sciences). Techniques such as digital storytelling, augmented reality reconstructions, or dramatizations can be used to present findings, thereby highlighting the human dimension of heritage alongside its technical achievements (Al-Maamari, 2020, 2022; Oman Vision 2040, 2019).

Teacher Interviews and Insights

An exploratory qualitative design was adopted to examine Omani teachers' perceptions of the Heritage-Based STEAM+S framework. Twenty social studies teachers were purposively selected to ensure diversity in years of teaching experience, grade levels taught, and prior exposure to innovative pedagogy. The sample represented both basic and post-basic education, thereby reflecting the broader structure of Oman's educational system (Al-Balushi, et al.. 2022).

A semi-structured interview protocol was developed and informed by prior research on STEM/STEAM integration in social studies and science education (Shahat, 2022; Shahat et al., 2024c). The protocol was designed to capture teachers' perspectives across six domains: their knowledge and awareness of STEM/STEAM, the applicability of such approaches in social studies, perceived challenges, pedagogical practices and strategies, relevant STEM/STEAM elements, and examples of added value. Each interview, conducted in Arabic, lasted between 30 and 45 minutes and was audio-recorded with participants' consent before being transcribed for analysis.

Thematic analysis was employed to analyse the data, guided by a systematic coding process (Creswell, 2019; Field, 2009). During open coding, descriptive codes were generated directly from the data, including phrases such as *"heritage relevance," "curriculum overload," "digital tools,"* and *"identity pride."* Axial coding followed, clustering related codes into broader categories for instance, curriculum overload and time pressure were merged into the category of systemic constraints. Selective coding then allowed these categories to be linked to the overarching research questions, with systemic constraints and training needs, for example, converging into the core theme of implementation challenges. The coding process adopted a hybrid approach, combining deductive strategies based on the interview protocol with inductive strategies that captured emergent insights, such as alignment with Oman Vision 2040 (2019).

NVivo 12 software was used to facilitate the coding process, enabling the organization, retrieval, and comparison of data across cases. The software also supported the creation of coding matrices that made it possible to trace how descriptive codes clustered into categories and themes, thereby enhancing analytic transparency. To ensure consistency, two transcripts were manually double-coded and then cross-checked within NVivo, thereby strengthening intercoder agreement and methodological rigor.

Several strategies were employed to ensure the study's trustworthiness. Credibility was achieved through member checks, whereby three participating teachers reviewed the interpretations to validate their accuracy and authenticity. Dependability was maintained by ensuring coding consistency through the double-coding process. Confirmability was supported by keeping a detailed audit trail of coding decisions, ensuring transparency and accountability in the analytic process. Finally, transferability was addressed by providing thick description of the Omani heritage-based educational context, allowing readers to assess the applicability of findings to other educational and cultural settings (Fosnot, 2013; Vygotsky, 1978).

The coding process generated five overarching themes, each supported by categories, illustrative codes, and insights from the interviewed teachers. The first theme, knowledge and awareness of STEM/STEAM, revealed varied levels of teacher understanding. Some participants demonstrated only a limited conception, with one explaining, “STEM is only math and science” (T3). Others displayed moderate awareness, recognizing its interdisciplinary nature and describing it as “integrated disciplines” (T11). A smaller group articulated a more advanced perspective, emphasizing the inclusion of cultural and artistic dimensions, as highlighted by one teacher who noted, “STEAM must include heritage and arts” (T16). Overall, awareness ranged widely, with only a minority explicitly identifying the heritage dimension.

The second theme, applicability in social studies, reflected a strong consensus among participants that the subject provides fertile ground for STEM integration. Geography was repeatedly identified as a natural entry point, with one teacher commenting, “GIS and mapping make lessons more interactive” (T7). Heritage contexts, such as the aflaj irrigation systems, were also seen as opportunities to merge engineering and environmental studies, as another participant explained: “We can explain aflaj irrigation as both a historical and engineering achievement” (T14). Others noted that demography provides a valuable domain for integration, using “population statistics to show links between math and society” (T9).

The third theme, challenges in implementation, highlighted several systemic barriers. Teachers frequently mentioned the problem of time and curriculum overload, with one stating, “The syllabus is too dense for projects” (T2). Others pointed to resource shortages, particularly in relation to digital tools, remarking that, “We don’t have VR or AR tools to make heritage come alive” (T18). A lack of professional development was another recurring concern, as one participant admitted, “There are no workshops on how to apply STEM in social studies” (T5). In addition, teachers raised the issue of assessment misalignment, with one observing, “Exams don’t fit projects, so we avoid them” (T12).

The fourth theme, practices and strategies, revealed that many teachers are already incorporating STEM-related approaches, albeit often unintentionally. Some described the use of digital tools, such as “Google Earth to teach geography” (T8), while others shared examples of project-based learning, including “building fort models” (T10) and “team projects where each student had a role” (T4). Teachers also referred to simulations of real-world problems, such as “disaster simulations to explain natural hazards” (T15). These accounts suggest that even in the absence of structured training, teachers are experimenting with approaches aligned with STEAM+S principles.

Finally, the fifth theme, cultural identity and citizenship, emerged as a particularly strong area of emphasis. Teachers repeatedly emphasized that heritage-based learning instils pride and strengthens identity. As one participant expressed, "Students felt proud of forts because they realized our ancestors used engineering long before modern science" (T6). Others linked heritage learning with broader national priorities, stating, "Heritage aligns with sustainability goals and Oman Vision 2040" (T13). Collectively, teachers emphasized that embedding heritage into STEAM+S not only deepens identity formation but also equips students with future-ready skills, thereby bridging tradition with innovation. Table 1 provides an illustrative sample of the coding process used in this exploratory qualitative study, showing how descriptive codes were clustered into categories and broader themes.

Table 1. Coding Process from Teacher Interviews

Theme	Categories	Example Codes	Illustrative Quotes (Teacher Codes)
Knowledge & Awareness	Limited, Moderate, Advanced awareness	"STEM is only math and science"; "Integrated disciplines"; "STEAM must include heritage and arts"	"STEM is only math and science" (T3); "Integrated disciplines" (T11); "STEAM must include heritage and arts" (T16)
Applicability	Geography, Heritage, Demography	"GIS and mapping"; "aflaj irrigation"; "population statistics"	"GIS and mapping make lessons interactive" (T7); "Aflaj irrigation is both historical and engineering" (T14)
Challenges	Curriculum overload, Resource gaps, Training needs, Assessment misalignment	"Syllabus too dense"; "No VR/AR tools"; "No workshops"; "Exams don't fit projects"	"The syllabus is too dense for projects" (T2); "We don't have VR/AR tools" (T18)
Practices & Strategies	Tech use, Project-based learning, Collaboration, Simulations	"Google Earth"; "Fort models"; "Team projects"; "Disaster simulations"	"Google Earth to teach geography" (T8); "Students loved building fort models" (T10)
Identity & Citizenship	Pride in heritage, Oman Vision 2040, Heritage as tool	"Proud of forts"; "Ancestors used engineering"; "Heritage aligns with sustainability"	"Students felt proud of forts" (T6); "Heritage aligns with Oman Vision 2040" (T13)

The coding analysis confirms that teachers view STEAM+S as a pedagogically powerful model. Results support the theoretical foundations:

- Constructivism: Students learn more deeply when tasks are authentic (e.g., fort models, aflaj studies).
- Sociocultural theory:'" Heritage contexts mediate learning, linking cultural identity to disciplinary knowledge.
- Design and creative thinking: Teachers saw project-based, iterative tasks as opportunities for innovation and resilience.

The findings also highlight the dual promise and challenge of STEAM+S. While teachers acknowledged its capacity to enhance engagement and cultural identity, they also underscored the need for institutional support including professional training, digital infrastructure, and curriculum flexibility. These findings align closely with Oman Vision 2040's dual emphasis on innovation and cultural sustainability.

Expected Outcomes

The Heritage-Based STEAM+S framework is designed to generate outcomes across three interconnected domains cognitive, affective, and societal. Findings from the semi-structured teacher interviews reinforced these projected outcomes, providing empirical validation and practical grounding for the model. From a cognitive perspective, the framework promotes higher-order thinking by engaging learners in authentic architectural challenges that demand problem-solving, analysis, and critical reasoning. Teachers noted that tasks such as modelling forts or analysing aflaj systems required students to integrate knowledge from multiple disciplines and apply it in practical ways. Design thinking was also fostered, as learners engaged in prototyping, testing, and iterative redesign, thereby cultivating systematic and innovative approaches to problem-solving (Razzouk & Shute, 2012; Nagai & Noguchi, 2003). In addition, creative thinking was strengthened through activities that encouraged fluency, flexibility, and originality in reimagining heritage structures and motifs (Guilford, 1967; Torrance, 1974; Beghetto & Kaufman, 2014). Teachers further reported that heritage-based approaches enhanced disciplinary mastery, deepening students' understanding of science, mathematics, engineering, and the arts by situating abstract concepts within culturally meaningful contexts (Pertiwi et al., 2024).

The affective outcomes were equally significant. Teachers emphasized that heritage-based lessons fostered stronger cultural identity and pride, as students developed a deeper appreciation for Omani heritage, reinforcing their sense of belonging (Al-Maamari, 2020, 2022). Motivation and engagement also increased, with teachers observing that students approached projects with greater enthusiasm and persistence compared to traditional lessons. Moreover, collaborative group tasks nurtured dispositions of teamwork, empathy, and communication, creating a learning environment where interpersonal skills were developed alongside academic competencies (Perignat & Katz, 2019; Vygotsky, 1978).

At the societal level, the Heritage-Based STEAM+S framework was recognized as aligning closely with the aspirations of Oman Vision 2040, which emphasizes innovation, identity, and sustainability (Oman Vision 2040, 2019). Teachers viewed it as a bridge between cultural sustainability and the acquisition of future-ready skills, enabling students to contribute to both national identity and global competitiveness (Al-Hushani, 2019; Ambusaidi et al., 2022). They also highlighted the potential for heritage-based projects to enhance community engagement by forging stronger ties between schools and local communities, as students interacted with cultural resources beyond the classroom (Cushner, 1992). Ultimately, the framework was seen as equipping learners with the dual capacities of technical expertise and cultural awareness, preparing them to navigate global challenges while remaining grounded in their heritage.

Taken together, the five emergent themes awareness, applicability, challenges, strategies, and identity map directly onto the three outcome domains projected in the Heritage-Based STEAM+S framework. Awareness reflects the cognitive domain, as it influences how teachers and students conceptualize interdisciplinary knowledge. Applicability extends into the societal domain, highlighting how social studies can embed heritage in authentic, community-relevant learning (Shahat & Al-Balushi, 2023). Challenges reveal barriers that must be addressed to achieve both cognitive and societal outcomes, particularly in relation to curriculum design and policy (Al-Mazrouei & Olayan, 2020). Strategies connect to cognitive outcomes, such as design and creative thinking, while also supporting affective outcomes, including collaboration, motivation, and engagement (Siekmann & Korbel, 2016). Finally, identity strongly resonates with the affective domain, reinforcing cultural pride and belonging, while simultaneously linking to the societal domain through its alignment with Oman Vision 2040 (2019). This mapping demonstrates how teachers' perspectives empirically validate the framework's potential to enrich cognitive, affective, and societal learning outcomes.

In summary, the Heritage-Based STEAM+S framework broadens conventional understandings of STEAM education by integrating heritage, culture, and identity into interdisciplinary learning. The teacher interview findings validate its potential to enrich cognitive, affective, and societal domains, while also underscoring the need for targeted professional development and access to digital resources (Al-Balushi, Al-Harthi, & Shahat, 2022). By positioning defensive architecture as both content and context, the framework ensures that learners acquire twenty-first century skills while sustaining national identity, thereby contributing simultaneously to innovation and cultural continuity.

Methodological Implications

The Heritage-Based STEAM+S framework presents significant methodological implications for curriculum design, instructional practice, and the evolving role of teachers in twenty-first-century education. By integrating science, technology, engineering, arts, mathematics, and social sciences through the authentic lens of defensive architecture, the framework demonstrates how culturally grounded, interdisciplinary approaches can transform both teaching and learning (Shahat & Al-Balushi, 2023; Ambusaidi et al., 2022).

Guiding Curriculum Design

This framework offers curriculum developers a model for integrating heritage-based themes into interdisciplinary units, connecting abstract disciplinary knowledge with real-world cultural contexts. Instead of organizing content in isolation, curricula can be designed around authentic problems and projects drawn from heritage architecture. For instance, units on measurement and geometry can be linked to fort design, while social studies and arts can emphasize the symbolism and historical significance of defensive structures. Such integration ensures coherence across subjects and fosters higher-order thinking, problem-solving, design, and creative skills. Importantly, it aligns with constructivist principles, enabling learners to construct meaning from authentic cultural contexts (Piaget, 1972; Fosnot, 2013), and with sociocultural theory, situating learning in socially and historically significant practices (Vygotsky, 1978).

Prior research in Oman has underscored the importance of embedding culturally authentic contexts into curriculum frameworks. For example, Shahat and Al-Amri (2023) highlighted the strengths and shortcomings of integrating STEM into science teacher preparation, while Shahat et al.

(2024a) emphasized the role of STEM-integrated experiences in enhancing elementary teacher preparation. These insights reinforce the methodological contribution of the STEAM+S model as a bridge between disciplinary content and cultural identity.

Integration into School Programs

The framework naturally supports project-based and inquiry-driven learning, where students collaborate on meaningful, open-ended tasks (Perignat & Katz, 2019). Practical applications include:

- Project-Based Units: Students design and test scale models of forts, analyse their structural stability, and present adaptations for modern use while preserving cultural authenticity.
- Inquiry Tasks: Learners explore critical questions, such as “Why were forts built in specific locations?” or “*How did climate and materials influence their construction?”*
- Virtual and Augmented Simulations: Technology can provide immersive experiences that allow students to explore reconstructed forts, experiment with structural modifications, or visualize historical scenarios (Shahat et al., 2024d).

Embedding such approaches into school programs exposes students to rich interdisciplinary content while also cultivating transferable life skills such as collaboration, cultural awareness, digital literacy, and creative problem-solving (Pertiwi et al., 2024; Al-Hushani, 2019).

Role of Teachers as Facilitators

The successful implementation of the Heritage-Based STEAM+S framework depends on a pedagogical shift in the teacher’s role–from knowledge transmitter to facilitator, designer, and mentor. Teachers are positioned as:

- Designers of learning environments, structuring tasks that connect disciplinary concepts to heritage contexts.
- Curators of cultural and digital resources, guiding students in exploring authentic heritage materials.
- Scaffolders of inquiry, posing critical questions and supporting iterative processes of design and creativity.
- Assessors of broader competencies, evaluating not only content mastery but also skills such as teamwork, innovation, identity formation, and cultural appreciation (Shahat et al., 2025b, c).

This reconceptualization of the teacher’s role resonates with design thinking pedagogy, where iterative processes of ideation, prototyping, and testing are embedded in classroom practice (Nagai & Noguchi, 2003; Razzouk & Shute, 2012), and with creative thinking frameworks, which encourage flexibility, originality, and elaboration in student responses (Guilford, 1967; Torrance, 1974; Beghetto & Kaufman, 2014). By adopting this stance, teachers create dynamic classrooms where learners are empowered to explore, innovate, and construct knowledge through culturally authentic, interdisciplinary experiences.

Contribution and Implications

This study contributes to educational research and practice on three interconnected levels theoretical, practical, and policy-related by advancing the scope of STEAM education and situating it within a heritage-based paradigm.

Theoretical Contributions

At the theoretical level, the study extends existing STEAM models by introducing the Heritage-Based STEAM+S framework, where the "S" represents social sciences with an emphasis on heritage, identity, and culture. Much of the global literature has traditionally positioned STEAM as a bridge between applied sciences and real-world problem-solving (Perignat & Katz, 2019; Siekmann & Korbel, 2016), but has often neglected the historical and cultural dimensions that shape knowledge construction. By embedding defensive architecture as an entry point for learning, the model situates constructivist (Piaget, 1972; Fosnot, 2013), sociocultural (Vygotsky, 1978; Al-Maamari, 2020, 2022), design thinking (Razzouk & Shute, 2012; Nagai & Noguchi, 2003), and creative thinking theories (Guilford, 1967; Torrance, 1974; Beghetto & Kaufman, 2014) within a single holistic framework. This integration positions cultural heritage not as peripheral but as central to interdisciplinary learning, thereby redefining the theoretical boundaries of STEAM education (Shahat & Al-Balushi, 2023).

Practical Contributions

On a practical level, the study offers educators and curriculum developers a heritage-based model for designing culturally relevant, interdisciplinary units. In the Omani context, defensive architecture forts, aflaj systems, and castles presents a compelling platform for project-based learning, inquiry-driven tasks, and immersive digital simulations that engage students in authentic exploration across disciplines (Ambusaidi, et al., 2022).

The model also offers scalable applications beyond Oman. For example:

- Roman aqueducts link engineering, mathematics, and environmental science.
- Islamic geometric art integrates mathematics, design, and cultural studies.
- Indigenous dwellings connect sustainability, anthropology, and technology.

Such examples illustrate that the Heritage-Based STEAM+S framework is a replicable and adaptable approach that educators worldwide can adopt to merge academic content with cultural relevance. By doing so, it bridges local traditions with global competencies, offering a roadmap for innovative and identity-affirming teaching practices (Al-Balushi et al., 2022). Embedding these global parallels highlights that the model is not limited to Oman but can be applied across various cultural and educational settings internationally.

Policy Contributions

At the policy level, the study aligns closely with the priorities outlined in Oman Vision 2040 (2019), which emphasize cultural sustainability, identity formation, and the development of future-ready citizens. The framework offers policymakers a concrete model for integrating heritage into national curricula in a manner that safeguards cultural continuity while promoting innovation and global competitiveness (Al-Hushani, 2019; Shahat et al., 2024c).

Moreover, the framework has international relevance. In a global context where nations grapple with balancing economic modernization and cultural preservation, the Heritage-Based STEAM+S framework provides a policy-relevant blueprint. It aligns with global agendas such as UNESCO's Education for Sustainable Development goals, which advocate for educational approaches that integrate sustainability, cultural awareness, and global citizenship (Bureau of International Education, 2015).

To conclude, the Heritage-Based STEAM+S framework makes a multi-level contribution. Theoretically, it redefines STEAM to include heritage and identity as essential dimensions of learning. Practically, it equips educators with strategies and exemplars for culturally relevant, interdisciplinary integration. At the policy level, it offers a model for aligning national priorities with global educational agendas. Together, these contributions highlight the transformative potential of the framework to reposition heritage from a static legacy into a dynamic resource for innovation, sustainability, and lifelong learning – both within Oman and across diverse international contexts.

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RETHINKING STEM EDUCATION

Theoretical and Sociocultural Frameworks

Rethinking STEM Education: Theoretical and Sociocultural Frameworks presents a concise yet comprehensive exploration of STEM education as an interdisciplinary and socially embedded field. Grounded in key theoretical perspectives such as constructivism, radical constructivism, cognitive load theory, and sociocultural theory, this edited volume connects foundational learning theories with contemporary instructional practices, curriculum design, and assessment approaches. The book adopts a holistic perspective by positioning mathematics as a core integrative component of STEM, examining technology as a transformative force in learning and assessment, and emphasizing inclusive and formative evaluation practices aligned with 21st-century skills. Beyond pedagogy, it situates STEM education within broader sociocultural, ethical, and ecological contexts, addressing themes such as community engagement, responsible innovation, environmental sustainability, and culturally grounded STEAM+S frameworks. Designed for researchers, educators, and policymakers, this volume offers a theoretically informed and socially responsive perspective on rethinking STEM education for a rapidly changing world.

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