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Towards a Socio-Constructivist Didactic Model for Integrated STEM Education

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Abstract

As science education shifts toward integrated STEM (Science, Technology, Engineering, and Mathematics) approaches, guidelines for designing teaching and learning episodes that integrate curricular content and procedures from multiple disciplines become increasingly in demand. The existing plethora of conceptualizations of STEM makes difficult such an endeavor, leading to ill-defined lesson plans focused on only two –mainly science and technology or science and mathematics– out of the four STEM disciplines. The question addressed, therefore, is how the integrated STEM approach could be translated into classroom practices that integrate the four STEM disciplines in a way that is consistent and coherent with elementary education curricula. This manuscript advances a theoretically informed didactic model for the design and implementation of integrated STEM in elementary education. The article discusses how the model uses socio-constructivist principles to establish intentional and explicit connections between STEM disciplines via scientific inquiry, engineering design, and computational thinking practices. The model is rooted in learning theories developed by Piaget, Vygotsky, Ausubel, and Bruner and could serve as a roadmap for educators and researchers designing integrated STEM lessons. Future empirical research testing the model is warranted.

Keywords Integrated STEM · Scientific inquiry · Engineering design · Socio-constructivism

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Introduction

In recent years, the STEM acronym emerged in the educational landscape and increasingly monopolized the research being conducted in science education. Likewise, its use in article titles, conferences, and policy documents is greatly proliferating. Thus, coining the STEM acronym seems to be a *conditio sine qua non* to denote innovative and quality educational proposals. Over the years, this materialized into the demand to adopt approaches that integrate the four disciplines of the acronym into a single teaching-learning episode or lesson plan. However, although this approach, called integrated STEM, has taken on a sense of urgency, its research agenda suffers from several critical limitations: there is no clear conceptualization of what constitutes integrated STEM and how to best implement it in the educational system. A common operational definition is still missing (Breiner et al., 2012) and research about its implementation is characterized by "(…) inconsistent use of language, failure to define terms, and lack of a theoretical model for understanding integrated STEM education" (Honey et al., 2014, p. 138). Due to the plethora of conceptualizations, lack of cohesive understanding, and evidence-based programs, some critical voices point to a *STEM-ification* of science education and consider the use of such an acronym as an "(…) ideological positioning of science education rather than anything evidence-based" (Carter, 2017, p. 2). Indeed, integrated STEM is at risk of being considered only as the neologism for science education. Consequently, there is a need for a common language in both educational research and practice.

Against this background, this article introduces a socio-constructivist didactic model aimed at guiding the design of lesson plans consistent with the integrated STEM discourse and elementary education curricular demands. In doing so, this study aims to contribute to the educational literature concerned with questions such as *How should STEM be conceptualized?* and, most importantly, *how should STEM be translated into educational practice?* Specifically, this article focuses on the following overarching research question:

- How could the integrated STEM approach be conceptualized and translated into classroom practices that integrate the four STEM disciplines in a way that is consistent and coherent with elementary education curricular demands?

To do so, the article is structured as follows. After summarizing the origin of the STEM acronym and the current definitions of integrated STEM in the literature, the limitations inherent in conceiving it as a *teaching methodology that integrates two or more disciplines* are discussed. We argue that such definitions increase confusion about the novelty and appropriateness of the educational proposals developed under the STEM umbrella, hence hindering the potential of integrated STEM to improve educational practice. Next, a conceptualization of STEM as an educational paradigm[1] is advanced, which would allow a parsimonious operationalization of integrated cur-

[1] In this article, *educational paradigm* refers to the set of beliefs and principles underlying classroom practice (i.e., the worldview underlying an educational discipline). On the other hand, *teaching approach* refers to the strategies and procedure used to implement such worldview (e.g., inquiry).

ricula through different long-standing and effective teaching strategies and socio-constructivist learning principles. Finally, a didactic model is proposed to aid the design of lesson plans aimed at integrating the four STEM disciplines in a consistent manner to their conceptualization in educational curricula. To justify its relevance and appropriateness, references are made to how the curriculum standards conceptualize these disciplines. To do so, we focus on the Next Generation Science Standards (NGSS Lead State 2013), arguably the source from which the vast majority of international curricula draw, and the context (i.e., the United States) in which STEM originated. Also, references to the Spanish curricula (context of the authors) are included. Finally, to support its validity from a psychological standpoint, the didactic model is analyzed in the light of constructivist and socio-constructivist principles postulated by Piaget (1974), Vygotsky (1979, 1981), Ausubel et al. (1982), and Bruner (1961, 1966).

Conceptualization of Integrated STEM Education

Origins of the STEM Acronym

The STEM acronym dates back to the 1990s when the National Science Foundation (NSF) used it as a "(…) strategic decision made by scientists, technologists, engineers, and mathematicians to combine forces and create a stronger political voice" (STEM Task Force Report, 2014, p. 9). This acronym attracted educational policy attention after the publication of the *Rising Above the Gathering Storm* report (NAS & IOM 2007) which argued that the advantages of the United States in terms of innovation and technological progress have begun to diminish in the last decade. The second edition of such a report painted "a daunting outlook for America if it were to continue on the perilous path it has been following in recent decades concerning sustained competitiveness" (NAS & IOM 2010, p. 2). While other nations made significant progress in the STEM disciplines, the United States' ability to compete effectively had deteriorated further, which calls for greater emphasis on the development of educational programs for the promotion and retention of talent in Science, Technology, Engineering, and Mathematics disciplines (Bybee, 2010; STEM Task Force Report, 2014). Therefore, from a policy perspective, STEM rapidly became a slogan that aims at fueling international competitiveness by fostering more graduates in these disciplines and recruiting a strong STEM workforce (Lyons, 2020; Toma & García-Carmona, 2021, Toma, 2021).

Definitions of Integrated STEM

To access financial grants devoted to projects promoting such a discourse, the STEM acronym became widely adopted in the educational landscape worldwide and rapidly acquired a wide spectrum of meanings and conceptualizations. Indeed, in their literature review, Johnson and Czerniak (2023) examined STEM education. They argue that STEM is a global movement, led by the USA and increasingly followed by many countries in Asia and Europe. They also note that countries like Australia and some

African nations have adopted this trend in their educational reform plans. Indeed, while the acronym started as a political discourse for national and state policies, it quickly began to be coined by educators and researchers as an educational movement with the ambitious goal of increasing the number of students pursuing STEM-related careers (Tanenbaum, 2016; Wang et al., 2011; for a review, see Martín-Páez et al., 2019). Therefore, from an educational standpoint, STEM is being conceptualized through a broad continuum of diverse, and sometimes contradictory educational initiatives, that move from a greater emphasis on STEM coursework through the improvement of science and mathematics curricula, to recent conceptions that refers to STEM as a global call to abandon the individualized treatment of each discipline in favor of the adoption of integrated approaches that emphasize integration across STEM school subjects and disciplines (Bybee, 2013; English, 2016; Kelley & Knowles, 2016). Hence, integrated STEM, as would call it proponents of this conceptualization, refers to STEM as the integration of these disciplines to closely resemble how STEM knowledge is developed and used in real life. It is argued that "STEM content should not be taught in isolation, but rather in a way that reflects how STEM knowledge is used outside of school; this knowledge is further contextualized or driven by some problem or issue" (Dare et al., 2018, p. 4).

In this sense, most definitions of integrated STEM education refer to it as a *teaching approach* that explores the connection between at least *two* STEM subject areas. While STEM education nominally incorporates all four disciplines, it often focuses primarily on science, potentially compromising the holistic understanding intended by the acronym. Indeed, Sanders (2009) defined integrated STEM education as a teaching approach that explores the connections among any two or more of the STEM subject areas, and/or between a STEM subject and any other school subjects. Similarly, Moore et al. (2014) referred to STEM education as "(…) an effort to combine *some* or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit or lesson that is based on connections between the subjects and real-world problems" (p. 38, emphasis added). In their influential conceptual model for integrated STEM education, Kelley and Knowles (2016) conceptualized it as "(…) the *approach to teaching* the STEM content of *two or more* STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" (p. 3, emphasis added). Likewise, Johnson et al. (2016) defined STEM as the *didactic use* of engineering design and thinking as means of exploring technologies through the application of mathematics, science, and/or other disciplines (e.g., social sciences, English/language arts). Martín-Páez et al. (2019) provided a definition for STEM based on a systematic review of the literature. Thus, they conceived STEM education as "a *teaching approach* that integrates content and skills specific to science, technology, engineering, and mathematics" (p. 815, emphasis added). More recently, Roehrig et al. (2021) proposed a comprehensive framework for integrated STEM education, outlining seven key characteristics: real-world problem-solving, engineering design engagement, context-based and content-integrated learning, authentic STEM practices, twenty-first-century skill development, and explicit connections between STEM careers and real-world problem solutions. In short, the definitions of integrated STEM education reveal a gap between the STEM acronym and the actual integration of the disciplines. There is a discrepancy between the STEM acronym and the actual practice of integrated STEM education, which often involves only two or more, but not necessarily all, of the STEM disciplines. Likewise, there seems to be a consensus on defining STEM as a *teaching approach*.

Limitations of Existing Definitions

While the common definitions of STEM resemble a *teaching approach* that integrates *two or more* disciplines into one unit (with few exceptions, e.g., Martín-Páez et al., 2019), the lack of a didactic model of how this integration should be translated into classroom practice has led to using this acronym in empirical studies addressing solely one discipline in isolation, thus being inconsistent with recommendations and not explicitly addressing the integration of the four disciplines (Martín-Páez et al., 2019; Toma & García-Carmona, 2021). Amidst this situation, several critical voices complain that STEM is being promoted at the expense of an operational definition. For some authors, STEM represents a deficient educational model that does not advance in the resolution of the problems faced by science education (Zeidler, 2016). For others, STEM seeks to align school science curricula in a direction "(…) that reinforce and legitimize a neoliberal hegemony of global competition and capitalist expansionism" (Weinstein et al., 2016, p. 201).

In an attempt to disentangle the meaning of STEM, Akerson et al. (2018) concluded that STEM is a "(…) socially constructed label that is in response to economic and global pressure" (p. 5) and that the advent of the STEM movement is reducing attention to other important aspects of science education, such as the teaching of nature of science. On the other hand, on reflecting on the characteristics of STEM as a *teaching approach*, Perales and Aguilera (2020) argued that STEM is based on the enduring Science-Technology-Society (STS) educational movement, however, its contributions to science education are scarce, concluding on the need to develop theoretical models that support the didactic transposition of integrated STEM education. Similarly, in our previous publications, we argued that STEM as a *teaching approach* is not sustained by any theoretical or empirical body that supports its relevance and didactic effectiveness (Toma & García-Carmona, 2021).

In addition to all these criticisms, it should be added that defining STEM as a *teaching approach* aimed at the *integration of two or more* disciplines resembles long-standing efforts promoted for decades in science education research. In this sense, the notion of curricula integration is not new and dates back to the 40s when the Eight-Year Study about the reconstruction of the secondary school curriculum proposed student-centered, cross-disciplinary approaches that addressed the need for making connections across subjects (Aikin, 1942). Likewise, there are substantial educational precedents that attempted such curricular integration, with efforts championed by the Science and Mathematics integration (S&M) and STS movements, whose effectiveness is at best equivocal (Bennett et al., 2007; Czerniak et al., 1991; Czerniak & Johnson, 2014). Hence, one wonders whether STEM, following such a definition, should be considered a new approach at all and if it adds any value to science education (Anderson, 2020; Lyons, 2020; Toma & García-Carmona, 2021).

Conceptualizing Integrated STEM as an Educational Paradigm

Despite all these limitations, STEM is very much alive and more present in education than ever before. If we are to advance the ubiquitous journey of the STEM agenda, it is paramount to first articulate a coherent conceptualization of such an acronym and develop didactic models that would help transfer it into classroom practice. In this sense, it is the author's understanding that conceiving STEM as a *teaching approach* is not without problems since self-named STEM studies use many different *teaching approaches*, such as inquiry, project-based learning (PBL), engineering design process, or computational thinking to deliver STEM units or lessons (Kelley & Knowles, 2016; Li et al., 2020; Shahali et al., 2017; Toma & Greca, 2018). Therefore, integrated STEM may be better conceived as an educational paradigm rooted in the long-standing tradition of curricula integration, aimed at establishing *connections* between Science, Technology, Engineering, and Mathematics to explicitly reflect on the synergistic relationship that exists between such disciplines in real life. Such a paradigm should not be restricted to the integration of two disciplines (since this resembles existing efforts such as S&M) but as the *connection*[2] of all disciplines representing its acronym.

Such a conceptualization of STEM education differs from the existing ones in several ways. First, STEM is conceived as an educational paradigm instead of a teaching approach. According to the NSTA position statement about STEM education, STEM "(…) gives students opportunities to see the *connection* between the content they are studying and the application of that content in authentic and relevant ways" (NSTA Board of Directors, 2020, emphasis added). Therefore, conceptualizing STEM as an educational paradigm would allow the development of research studies testing different *teaching approaches* (e.g. inquiry, engineering design, problem-based learning) for such an endeavor. In other words, it will be possible to determine which teaching approaches are the most appropriate for establishing, in a meaningful and non-trivial manner, the relationship between the four STEM disciplines and their application to real-life situations and problems.

Second, this conceptualization proposes the connection of the four disciplines identified by the acronym, which would help differentiate the STEM educational paradigm from other approaches to curricular integration existing in the literature. Given that engineering is not a formal elementary school subject in most countries (Gago et al., 2014), integrated STEM should focus on the curricular content of both the science and math school subjects, enhanced with the inclusion of technology and engineering practices, which refers to the knowledge and skills that engineers use to design and build models and systems useful for solving problems. This implies that technology should be conceptualized through an instrumental-engineering lens (cf., Feenber, 2017), portrayed as both making and using artifacts and instruments that can enhance the development of scientific knowledge and the engineering applications,

[2] It should be noted that "connection" is used instead of "integration", given that meaningful integration requires a strong disciplinary background in each of the disciplines, something that even STEM professionals do not possess (Lyons, 2020; Toma & García-Carmona 2021). This aspect is further discussed throughout the manuscript.

and vice versa (e.g., science knowledge and engineering advancement improve available technology). While epistemologically limited, this conceptualization is consistent with contemporaneous worldwide curricula reforms (e.g., in the USA, the Next Generation Science Standards; in Spain, the LOMLOE, 2020) and could pave the way toward translating the STEM discourse into classroom practice.

The third differentiating feature of the STEM conceptualization proposed is related to *integration*, defined as "(…) working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines" (Honey et al., 2014, p. 52). Thus, interdisciplinary STEM learning episodes should aim at reducing the restrictions and boundaries between *each* discipline composing the acronym to enhance the relationship between their concepts, procedures, and skills (i.e., establish meaningful connections). This article advocates that such connections to be done such that to not undermine the idiosyncrasies of each discipline, thus allowing students to understand the differences and similarities between them, as well as how these disciplines operate in real life for problem-solving. For example, a unit establishing explicit connections between the curricular contents of science and technology disciplines could develop an understanding of how technology could drive the development of scientific knowledge and how, at the same time, new scientific knowledge contributes to the improvement and refinement of existing technology.

Development of the Didactic Model

Having described the conceptualization of STEM as an educational paradigm, and having justified how to conceptualize each discipline and its integration into a single teaching and learning episode, the didactic model to guide this task is presented below. First, some socio-constructivist principles that form the basis of the model are reviewed. Subsequently, the model is presented, describing how the four disciplines are integrated. Finally, the model is reviewed in light of the reviewed socio-constructivist principles, demonstrating its coherence and alignment with such principles.

Socio-Constructivist Learning Theories

This section revises the main postulates of Piaget (1974), Vygotsky (1979, 1981), Ausubel et al. (1982), and Bruner (1961, 1966), which served as psychological underpinnings for the educational reforms over the last decades. As a result, we believe they still constitute valuable elements or ideas for guiding the didactic transposition of integrated STEM education.

Assimilation and Accommodation

Jean Piaget (1974) conceived intellectual development as a dynamic, active process in which the subject incorporates new information into existing cognitive schemas. He proposed two principles guiding intellectual development. The first principle, known as *assimilation*, refers to the process through which the new information is shaped to fit into existing schemas. Yet, during the second principle, named *accommodation*, existing schemas are modified to assimilate new information. This requires that the new information be sufficiently demanding to create a *disequilibrium* in the existing schemas, which will adapt until a status of equilibrium is established. Hence, accommodations of new information will not be achieved if learning episodes are too demanding and differ too much from the student's existing schemas.

Social Interaction

Lev Vygotsky (1979, 1981) postulated that an individual's development is influenced by two different factors. On the one hand, there are *fundamental processes* that are of biological origin and play a minor role. The *higher psychological processes*, on the other hand, have sociocultural roots. Thus, an individual's development is viewed as a social process that is aided by adults or other agents regarded as more competent, named Most-Knowledgeable-Others (MKO) who assist the student in the assimilation of the socially and culturally established system of symbols (e.g., curricular content). Vygotsky asserted this happens through learning scenarios near the Zone of Proximal Development (ZPD), the space between what a learner can achieve by himself and what a learner can achieve with the assistance of an MKO. Learning episodes should, therefore, stimulate peer interaction among students of varying ability levels, guided by the MKO teacher who designs organized and scaffolded learning settings immersed in the ZPD.

Meaningful Learning

David Ausubel et al.'s (1982) postulates focus on ensuring students' meaningful learning, thus attributing meaning to the new information presented. He drew importance to students' prior ideas which serve as a basis for learning the new information. Therefore, meaningful learning occurs when the newly-presented information interacts with the existing cognitive structure, allowing it to acquire meaning and be fully integrated. This requires structured teaching episodes that consider the student's prior knowledge, as well as the progressive presentation of new information and the use of scaffolding to make connections to prior knowledge. Relevant learning material and a positive attitude or predisposition to learn are also required.

Discovery Education

Jerome Bruner (1961, 1966) emphasized that learning shouldn't be limited to memorization but should help students develop problem-solving skills. He introduced the concept of *discovery education*, through which students actively and constructively learn how things work. The teacher must design relevant assignments that help students apply what they're learning by using scaffolding, defined as the help a learner receives from peers, adults, materials, and technology in a teaching and learning situation.

Presentation of the Didactic Model

Based on the preceding discussion and argumentation, Fig. 1 presents a didactic model for designing interdisciplinary STEM didactic units. In short, using a two-phase procedure, students engage first in scientific practices to develop scientific knowledge and understanding of the phenomenon under study (Phase 1: knowledge development). Then, students get involved in engineering practices to apply this knowledge to the design and development of a technological solution for the phenomenon under study (Phase 2: knowledge application), thus explicitly tackling the interconnection between the STEM disciplines and discovering the relevance of each one. Finally, mathematics and technology are explicitly addressed in both phases through data collection and analysis of the results.

The image illustrates the characteristics of STEM learning episodes, delivered through two phases aimed at the development of scientific knowledge and inquiry skills (Phase 1) and engineering design of models and technological solutions (Phase 2) to a real-world, interdisciplinary, problematic phenomenon. Specifically, the model conceives scientific and engineering practices as the backbone of a STEM unit, addressed through a real-world problem that stems from the school science and mathematics curricula and that is introduced to the students at the start of the unit. The first phase is devoted to developing scientific knowledge, understanding, and skills related to the phenomenon under study by engaging students in scientific practices. Next, the information from the first phase is used in the second phase for the design, construction, and testing of models and technological features or processes that may solve the initial real-world problem proposed at the start of the unit. The inclusion of both scientific and engineering practices into one unit would help tackle the interconnection between science and engineering (NGSS Lead State 2013).

Mathematics and technology are included in both phases. On the one hand, following an instrumental conceptualization, technology is represented by the devices

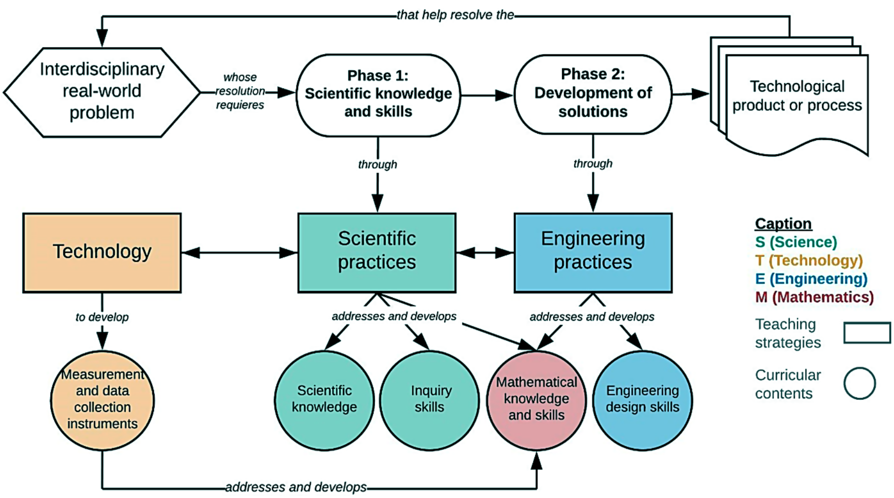

Fig. 1 Didactic model for integrated STEM education

used during the scientific and engineering practices, and also by the solutions proposed at the end of the unit. As already noted, this proposal is consistent with how most curricula worldwide conceptualize technology at K-12 levels. For example, the Next Generation Science Standards expect students to "use laboratory tools connected to computers for observing, measuring recording, and processing data" (NGSS Lead States, 2013, p. 58). In the Spanish context, the Organic Law for Educational Improvement (LOMCE, 2013) argued that technology should be used as a resource for learning curricular subjects since it facilitates the establishment of relationships between the different curricular contents; a conception that is perpetuated in the newest educational reform (LOMLOE, 2020). It also states that technology should be used to carry out interactive simulations and to represent phenomena that are difficult to carry out experimentally.

On the other hand, mathematics curricular concepts and skills are essential for the development of scientific investigations and the design of technological solutions. This way, mathematics knowledge, and skills are developed in real-world contexts where they became meaningful and relevant. For example, mathematics is essential throughout the STEM unit for the collection and interpretation of data during scientific practices. Likewise, mathematical reasoning is essential during the prototype design phase of engineering practices (Cunningham, 2018). This conceptualization and portrayal of mathematics in the STEM didactic model are also in line with existing curricula conceptualizing mathematics as a tool for the understanding of science and engineering practices: "Students are expected to use mathematics to represent physical variables and their relationships and to make quantitative predictions (…)" since "mathematics often brings these two fields together by enabling engineers to apply the mathematical form of scientific theories and by enabling scientists to use powerful information technologies designed by engineers" (NGSS Lead States, 2013, p. 58, 65).

Validity of the Model from a Socio-Constructivist Perspective

Table 1 lists the socio-constructivist principles discussed and their educational implications that have been taken into account for the development of the didactic model for integrated STEM education.

In this sense, socio-constructivist authors argue that learning takes place by the interaction between the learner and environmental factors that can enhance or undermine it. Therefore, it is essential to establish realistic learning episodes where the learning task and concepts are delivered through situations that are relevant to the learner's previous experiences. Consequently, in the proposed model, learners are engaged in real-world situations where the new knowledge is contextualized and used, and the teaching strategies (i.e., scientific and engineering practices) assist learners in actively exploring and building their understanding.

On the other hand, since Piaget's theory conceives development through the process of assimilation and accommodation of learners' schemas, the idea that teaching should be adapted to the cognitive development of the learner is fundamental. This notion relates to the need to introduce certain concepts of increasing difficulty to create disequilibrium in existing schemas; yet, not too difficult so that the new informa-

Table 1 Implications of socio-constructivists learning theories for the didactic model proposed

Key principles	Educational implications
Piaget	
1. Assimilation and accommodation of new knowledge	1.1. The real-world problem includes carefully selected key concepts and procedures that are adapted to learner's biological stage of cognitive maturation
	1.2. The unit starts with a real-world problem aimed at creating disequilibrium in the existing cognitive structure 1.3. Students engage in active learning episodes (i.e., scientific and engineering practices) to foster assimilation of the new knowledge 1.4. The two phases allow students to develop knowledge and apply it to new situations to facilitate knowledge accommodation
Vygotsky	
1. Psychological development as a socially mediated process between advantage (i.e., MKO) and fewer advantage individuals	1.1. Scientific and engineering practices foster cooperative learning 1.2. The teacher acts as a resource person (i.e., the metaphor of "teacher as a guide") 1.3. Each phase of the unit has clearly established goals
2. Cognitive development as the internalization and transformation of socially and culturally established a system of symbols	2.1. The educational curricula is introduced through authentic problems that creates opportunities for the system of symbols (i.e., STEM concepts and skills) to be internalized by the learners 2.2. Students participate in rich and engaging activities that foster conceptual understanding that are transferable to other situations and contexts
3. Zone of proximal development (ZPD)	3.1. Scientific and engineering practices are developed following scaffolding strategies
Ausubel	
1. Meaningful learning as the process of linking new knowledge to the existing cognitive structure	1.1. New concepts and skills are related to the existing cognitive structure of the learner through active teaching strategies and scaffolding strategies
2. The learner has an active role in this process	2.1. Teaching methodologies that actively engage student in the learning process by exploring, discussing, and critiquing the new information are used 2.2. By engaging in scientific and engineering practices, students develop their own knowledge through questioning, exploring, elaboration and co-construction of a solution to the authentic problem underpinning the unit.
3. Emotional disposition of the learner	3.1. Scientific and engineering practices are highly motivating for students
Bruner	
1. Discovery learning	1.1. The proposed model promotes students active and collaborative participation
	1.2. Students connect the new concepts with existing knowledge in authentic learning experiences
	1.3. During the unit, STEM concepts and skills are iteratively applied to different situations of increasing abstraction and complexity through both phases of the model

tion cannot be assimilated. Since developmentally appropriate concepts should be introduced to foster new cognitive assimilation and adaptation processes, students engaging in scientific (Phase 1) and engineering practices (Phase 2) will lead to cognitive conflicts (i.e., disequilibrium), understood by Piaget as situations that encourage the construction of new processes of assimilation and accommodation of the new information. Accordingly, and also consistent with Bruner's theory, the proposed model is student-centered and the acquisition of the content curricula takes place through a process based on discovery learning in which the teacher creates meaningful contexts and guides and facilitates this discovery through scaffolding.

As for Vygotsky's sociocultural theory, it has several implications related to the social environment in which the learning takes place. Given that higher mental processes originated because of social interaction, the proposed model fosters collaboration and discussion between peers through scientific and engineering practices. Social interaction should not only be embedded in activities with concise goals but also be extended over time for the internalization of shared systems, hence fostering cognitive development. Since this is a long and slow process, students can test and reflect on their new cognitive development and internalized systems in real environments and situations by increasing progressively the level of abstraction and complexity of the concepts introduced, such as it is done within the two phases proposed.

Educational Implication

This article leads to several implications for science education practice and research. First, there is a need to abandon the detrimental practice of coining the term STEM when only two disciplines are being addressed. To facilitate progress in this line of research, projects, studies and lesson plans should only be categorized as *integrated STEM* when they address, to some extent, the four STEM disciplines explicitly into the same learning episode. Indeed, educational studies developed under the STEM umbrella should be explicit about which disciplines are being connected and how is such a relationship between disciplines translated into classroom practice.

The second implication is related to the teaching approaches to be used when delivering integrated STEM lessons. In this sense, the didactic model advanced in this study proposes to actively engage students in scientific and engineering practices, bound by the use of technology and mathematical reasoning, which are the cornerstone for establishing explicit connections between the four STEM disciplines within a single unit. While the conceptualization here advanced describes the characteristics that an integrated STEM unit rooted in socio-constructivist learning theories should have, the model proposed is intended to be dynamic to adapt to the limitation of the educational system. Thus, it is not an advocate that all curricular content should be delivered following such an approach. Rather, the need for lecture-based teaching episodes is recognized, and therefore interdisciplinary projects and units are promoted for only those curricular contents that can be approached through real problems that are appropriate to student's cognitive development, and through which both the uniqueness and the interconnection of each STEM discipline can be made explicit and understood by students.

Third, although the idea of teaching science, technology, engineering, and mathematics in an integrated way is appealing and intuitively valid, many factors should be considered before blindly promoting such an approach (Lehrer & Schauble, 2020). Therefore, it is worth asking to what extent the design of a curriculum based on these integrated STEM principles is feasible. In this sense, the definition and didactic model advanced in this study could help develop integrated STEM units that can be used in research studies examining the viability and educational value of such an educational paradigm.

Finally, if integrated STEM is to be fully adopted in science education, the proposed didactic model has implications for in-service and prospective teacher professional development. While there is much research focused on improving science teacher practices using inquiry-based approaches, there is a gap in the literature on how to train teachers with the content knowledge and didactic content knowledge needed to implement integrated STEM lesson plans, especially since engineering practices are to be promoted by teachers who lack formal training in engineering (Akerson et al., 2018; García-Carmona & Toma, 2024). This is one of the reasons why the proposed didactic model is certainly guided by science, although accompanied by engineering practices. Therefore, this aspect represents one of the greatest challenges for the STEM conceptualization and didactic model here proposed, as this new educational paradigm aiming at curricula connection of four disciplines raises the need to completely revise and adapt teacher professional development plans.

Conclusions

There are many questions about integrated STEM that cannot be answered unless it is fully conceptualized. The literature has raised several criticisms and concerns about STEM, which we share and have also voiced previously (Toma & García-Carmona, 2021; García-Carmona & Toma, 2024) and throughout this manuscript. For us, the STEM discourse entails many aspects that warrant careful examination. We are skeptical about most self-proclaimed STEM initiatives, insofar their didactic implementation resembles longstanding science education practices of dubious merit. Furthermore, we also argue that STEM is being heavily promoted at the expense of robust evidence of its effectiveness and innovation. Hence, we are worried that this label is just a marketing strategy to get more funding and sell more products (e.g., robotics kits), rather than a genuine educational reform. In order for STEM education to meaningfully improve science education, its implementation must be guided by a systematic approach. A crucial initial step involves reaching consensus on a shared understanding of its conceptualization, followed by the development of didactic models for its transposition into classroom practice. This will enable future studies to rigorously evaluate the effectiveness of integrated STEM, if any (Toma, 2022).

Therefore, in this manuscript, we discusses major existing definitions of STEM education and proposes a conceptualization of integrated STEM as an educational paradigm instead of a teaching approach, which allowed the development of a didactic model rooted in socio-constructivist learning theories. The ideas of socio-constructivist authors, such as Vygotsky, remain relevant and influential for educational reforms worldwide, despite being developed many decades ago. Hence such a model could be useful in guiding the development of learning episodes that explicitly and meaningfully establish connections between science, technology, engineering, and engineering disciplines in line with how such disciplines are conceptualized in educational curricula.

Socio-constructivist learning theories emphasize the role of social interaction and collaboration in the construction of knowledge and meaning. Although these theories were developed in the 20th century, they are still relevant for science education teaching in the 21st century. This is because science is not a fixed body of facts, but a dynamic and evolving process of inquiry and discovery that requires students to engage in dialogue, argumentation, and problem-solving with their peers and teachers. By applying socio-constructivist principles, science educators can foster students' scientific literacy, curiosity, and creativity, as well as their critical thinking and communication skills.

The proposed didactic model, though, is not the only one that could be used, as was discussed throughout this article. Thus, in the literature, engineering design as the content integrator (Shahali et al., 2017) while others focuses on computer programming (Li et al., 2020). Future research determining the viability of each approach are needed. In addition, it should also be noted that technology and engineering are both conceptualized from a limited epistemological standpoint. The didactic model presented may be modified as we gain a better understanding of the epistemological aspects of technology and engineering that should be addressed in primary school. This limitation, however, should not be viewed as invalidating the proposed model, in so far it resembles educational curricula standards such as the NGSS and position statements such as the one advanced by NSTA.

In this regard, it is hoped that the conceptualization advanced in this paper could add to reversing the current trend in science education research consisting of incorporating the STEM acronym into projects and studies, regardless of whether or not it tackles the interconnections between the four STEM disciplines. This is certainly a commendable goal, so it is not expected, nor claimed, to have fully achieved this task. However, it is hoped that progress has been made towards conceptualizing integrated STEM education and developing didactic principles that guide the design of STEM teaching units that can be used to evaluate the appropriateness and effectiveness, if any, of such an educational paradigm.

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Declarations

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