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# On the practice of integrated STEM education as "poiesis"

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**ABSTRACT**

The value of science partly lies on the development of useful products for humanity's needs, but basic sciences cannot be said the "protagonists" of their obtention. Human history shows that these processes occur as a result of interactions between science and technology, mathematics, and engineering, as well as ethics and aesthetics. This network of disciplinary relationships facilitating the impact of scientific knowledge on human lives is at the center of discussions in the field of Science, Technology, Engineering, and Mathematics (STEM) education, and will be the focus of this article. Since the problems encountered in people's everyday activities cannot be solved with the knowledge and skill of a single discipline, there emerges an aim for general education to attain more holistic understandings required by human needs. Our conceptualization of STEM education, based on classical Greek philosophy, addresses this issue. We acknowledge that the traditional paradigm of monodisciplinary education, formed as a result of the separation of sciences over history, has been challenged in the last two decades with the rise of integrating approaches in science and technology education. STEM is consistently mentioned as a way for gaining the integrated knowledge and skills deemed important for the near future, but theoretical searches towards solving its basic problems are still ongoing and we take this as our general research problem. In this argumentative study, the philosophical approach proposed to shed light on STEM education practices is structured along two conceptual axes: integration of disciplines and inclusion of humanistic goals. Suitable foundations for our proposal are sought in Aristotelian philosophy: We use Aristotle's conception of a particular kind of human activity—poiesis, that aims to create "useful" and "aesthetic" products in order to propose an engineering "center" or "core" in the design of STEM school practices. Our model, labeled as "poietic" STEM, incorporates key elements of the nature of engineering; under the light of such a model, some aspects of what is called the "nature of STEM" are discussed. We conclude that, in an education envisaging more holistic approaches towards citizen literacy, it is necessary to connect the performance of STEM with responsible human interaction. In accordance with this requirement, our approximation to STEM centered on an epistemologically sophisticated conception of engineering makes room for fostering shared awareness in students.

**Key words:** STEM integration, humanistic goals for education, didactical model, Aristotelian poiesis, engaged human praxis

## INTRODUCTION

Many classifications of science (and of the specific scientific disciplines) can be found in the history of science. Such classifications are oriented by aims imposed by the philosophical and academic contexts in which they are formulated, rather than adapted to the solving of everyday practical problems. However, knowledge produced by the so-classified sciences needs to be interconnected in any process in real life that

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attempts at satisfying human requirements.

The knowledge and skills that citizens use in meeting life needs or solving life problems are intertwined in such a way that any separate discipline will usually result insufficient. Such knowledge and skills that result efficacious in citizens' activity should be acquired in education in a more holistic manner. A similar unity can be demanded to the scientific disciplines in the production of applicable theories. In the recent history of science, and perhaps without us educational experts being aware of it, a tendency towards integration can be recognized. The main lines of this ongoing quest for unity can be summarised as follows.

The search for a "system" of sciences can be traced back to the emergence of modern scientific theories in the late 18th century.[1] In this process, academic specialization of the sciences differentiating from one another brought about disconnections between them. A realistic diagnosis of this situation led to the search for ways and methods to establish tighter relations between sciences and phenomena. A vehement example of this search is the philosophical program of logical positivism (1920–1940). This kind of search resulted in unsuccessful attempts since the thesis of an underlying unity of sciences was based on naive ideas of one science covering another or reducing to the other.[2–5] However, in line with a global approach to this problem that Alatlı[6] refers to as a "revolution of integrative thought", it is observed that disciplines or fields of work that serve human interests are trying more and more to move away from closed specialization[7] and to work from a holistic platform.

In parallel with these epistemological changes, it was necessary to pedagogically classify the sciences in order to educate children, adolescents, and young people in about the same time period, the 19th century. Thus, the disciplinary disconnection that emerged as a consequence of science classification was reflected in education, bringing about fragmentation and reduction with the excuse of specialization. Markedly independent training in the separate disciplines became the rule. Different views on monodisciplinary, specialized teaching settled, while limited relations were established between curriculum areas. Research and policy in the educational sciences that tackle this theoretical framework of monodisciplinary teaching have generated some literature.[8] However, along this process, the fact that social needs have become more complex, partly as an effect of the developments in science and technology in the last half a century, has required the acquisition of skills and knowledge to respond to them.[9,10] Theoretical frameworks discussing the possibility of interdisciplinary perspectives in compulsory education emerged, recovering earlier attempts such as those proposed by 19th century theorists of progressive education Claparède and Decroly,[11] the United States philosopher John Dewey,[12] the science-technology-society movement,[13] or much more recently, Edgar Morin.[7]

At the present stage of science and technology education, concrete actions towards a more holistic approach to disciplinary knowledge and skills seem necessary to prepare the new generation for the world of the future.[14,15] In the last two decades, the conglomerate of Science, Technology, Engineering, and Mathematics (STEM) has stood out as a promissory and viable approach towards these desired integrations. In this article, we want to re-discuss the nature of integrated STEM education under the light of some powerful concepts from classical and contemporary philosophy. In particular, we are interested in Aristotle's notion of poiesis, which will be educationally defined as a collective activity that associates knowledge, practice, action, and emotion in the production of socially valuable products. The thesis underlying this article is that it can prove fruitful to include this kind of poietic activities in STEM education practices.

We take as our starting point the plea for attention issued by McComas and Burgin[16] in relation to the extreme paucity of sound philosophical underpinnings that they have detected in the literature supporting STEM. To name but two examples: there are very few STEM studies available[17] in which overarching educational goals such as autonomy and sociocultural awareness are taken as significant variables; and the so-called "integration problem" in actual STEM education applications is insufficiently treated, thus pointing at a theoretical vacancy in science and technology teaching.[18] Accordingly, in this article, we envisage to make some contributions toward the collective academic definition of a philosophical framework for STEM that helps clarifying its position in the field of contemporary education. As advanced, the preferred philosophical idea for our proposed foundations will be the concept of poiesis; we will use this concept with the following research aims: associating STEM with a recognized philosophical system, and cementing together different aspects of a model of humanistic integrative education.

## STEM AND STEM EDUCATION

The term "STEM" was chosen as a "pronounceable" abbreviation of the key disciplines of science, technology, engineering, and mathematics, but soon came to be used as a theoretical label to refer to (social, cultural, educational) events, policies, programs, or practices that involve these disciplines.[19] In a broad sense, STEM implies bringing together these disciplines (more generally, their associated fields of work or professions) for educational purposes, around problems related to the environment, economy, health, weather, agriculture, *etc*.[20] "STEM education" refers to an approach that seeks some degree of interdisciplinarity in the teaching processes in all levels of education.[21] STEM education aims to develop certain knowledge, skills, competence, and literacy in individuals through activities structured around the solution of "real life" problems using different subject areas. Undoubtedly, STEM conveys enormous potential for today's education, interest in this approach increases day by day, and the benefit of the application of "active" methodologies for students is given more and more value in academic studies.[8,22–24]

When we look at recent history,[25–30] the emergence of STEM in the United States is seen as a consequence of political and economic developments: these context factors have been directly impacting the educational systems of the country at least since World War II, and a political agenda for education was established at the turn of the century. Since then, STEM education, with rather transparent political and economic foundations (critically examined by Dana Zeidler),[31] has been rapidly spreading around the world, becoming now a globally accepted approach to technoscientific literacy.

Closely following Blackley and Howell,[32] the stages in the evolution of STEM can be summarized in Figure 1.

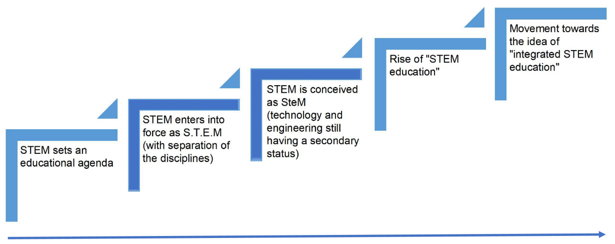


**Figure 1.** A postulated evolutionary process for STEM education, following Blackley and Howell.[32] STEM: Science, Technology, Engineering, and Mathematics.

It is seen in Figure 1 that a "model" of STEM education was only introduced relatively recently, and that the explicit advocation for an "integrative" or "integrated" version of this came in use as late as 2007. Additionally, it was around 2011 when the suggestion was raised of further integration of a variety of creative skills and content from other non-STEM disciplines (such as arts and humanities, computing and information processing, or management and entrepreneurship).

Integrated STEM education became the explicit foundation of official curriculum documents when the so-called Next Generation Science Standards were formally launched in the United States in the early 2010s.[33] Needs for qualification of the workforce, one of the factors that has given meaning to STEM education from its origins, have since then started to be more overtly defined.

## THE "INTEGRATION PROBLEM" IN STEM EDUCATION

Although there is consensus that STEM envisages an education that unites disciplines, there are no agreed-on definitions on the implementation of this desired unification.[8,34] Different proposals (even considered "models")[35] have emerged in the literature according to the number of "active" disciplines in the integration process and the ways in which this can be attained.[29] A current definition of integrated STEM gives emphasis to the use of different learning environments as contexts in which students can learn in more depth from science, mathematics, technology, or engineering while using varied pieces of information and resources in solving problems.[36] "Integrative STEM" is also a theoretical way to refer to technological, or engineering-design-based learning approaches[37] that deliberately integrate various science and mathematics education concepts and applications, with the potential of being expandable to other school courses such as arts, social sciences, and language.[27]

In spite of these definitions, Bybee[29] spots "uncertainties" in the plethora of available studies around the very concept of integration in STEM: some proposals focus on a single discipline aided by others; sometimes the recommendations aim at constructing links between the four areas; other publications conclude that all disciplines need to be seen as indistinguishable from one another.[38] In summary, the rhetoric associated with STEM moves within a shockingly ample spectrum ranging from single-discipline implementations to full "transdisciplinary" integration at a higher level of complexity. Based on Bybee's analysis,[29] Table 1 presents our understanding of some of these models.

We agree with Ortiz-Revilla *et al.* in their diagnosis that,[8] in spite of the many different perspectives on STEM integration, the rule is for science and mathematics to stand out due to their clear place in curricula for compulsory education, while technology and engineering, which were not directly involved in school programs until very recently, tend to be given much less prominence and a vaguer role. However, the National Research Council in the United States has critically highlighted engineering for more than a decade now, especially in the context of integrative STEM, emphasizing the need to use other disciplines (science, mathematics, and technology) as tools for engineering

**Table 1: A variety of possible STEM models, inspired by Bybee[29]**

| Model description | Symbolic representation |
|---|---|
| STEM is reduced to the teaching of a single discipline (usually science or mathematics) enriched with input from others | $\mathrm{STEM} \equiv \mathrm{S_{TEM}} \vee \mathrm{M_{STE}}$ |
| A STEM where science and mathematics stand out distinctly, while technology and engineering are blurred | $\mathrm{STEM} \equiv \mathrm{S.\ t.\ e.\ M}$ |
| STEM as a kind of science education that includes engineering, mathematics, and technology | $\mathrm{STEM} \equiv \mathrm{S} \supset \{\mathrm{T, E, M}\}$ |
| STEM develops the four disciplines with relative independence from each other | $\mathrm{STEM} \equiv \mathrm{S}\ldots\mathrm{T}\ldots\mathrm{E}\ldots\mathrm{M}$ |
| STEM connects science and mathematics through engineering and technology | $\mathrm{STEM} \equiv \mathrm{S} \leftarrow (\mathrm{T} \wedge \mathrm{E}) \rightarrow \mathrm{M}$ |
| STEM develops the four domains in a coordinated fashion | $\mathrm{STEM} \equiv \mathrm{S} \smile \mathrm{T} \smile \mathrm{E} \smile \mathrm{M}$ |
| A model of STEM combining two disciplines, where one is almost invariably science | $\mathrm{STEM} \equiv (\!(\mathrm{SE})\!) \vee (\!(\mathrm{ST})\!)$ |
| STEM seeks overlapping and complementation of the disciplines | $\mathrm{STEM} \equiv \mathrm{S} \cap \mathrm{T} \cap \mathrm{E} \cap \mathrm{M}$ |
| STEM aims at transdisciplinary integrations | $\mathrm{STEM} > \mathrm{S} \cup \mathrm{T} \cup \mathrm{E} \cup \mathrm{M}$ |

STEM: Science, Technology, Engineering, and Mathematics.

education.[39] This can be understood from the economic reasons emphasized in the recent history of STEM.

In this turbulent context, where innovation groups worldwide are testing a variety of integrative approaches, those using problem-based learning (PBL) stand out; their underlying pedagogy is solid and pertinent. However many instantiations of PBL STEM only feature two or three disciplines in practice.[40] The integration of social sciences, humanities, and arts (to a lesser extent) still remains a practical problem for teachers. In this article, we will understand PBL as a means of disciplinary integration in STEM applications; a careful selection of the problems will then be the key ingredient to go beyond the basic science, technology, engineering, and mathematics and to aim at student gains in the cognitive, linguistic, social and emotional domains.

In coherence with this, we will align ourselves with authors that expect STEM to be a meta-discipline providing the machinery for full integration,[41] while acknowledging that, in today's use, STEM as a rule more modestly points at moderately integrated curricula.[42] According to Pitt,[43] some scholars still define any innovative endeavor involving science, technology, engineering, or mathematics as STEM, while others argue that the essence of current STEM is to explicitly connect components of two or more learning areas. In any case, it is clear that, for STEM to be a valuable contribution, it must prove to be more than the sum of its parts. In this context, meaningful integration of content and of learning objectives from more than one STEM discipline should be taken as the desirable goal.[44] However, the uncertainty about the very nature of integrated STEM[8] makes it unlikely to reach closed definitions of sustainable inter- and trans-disciplinary integrations. In order to attempt definitions of this kind, it is necessary to first make a critical analysis of the nature of integrated STEM education.

## TWO MAIN CATEGORIES OF PROBLEMS REGARDING STEM

When the historical and current situations of STEM are examined in detail, a number of questions, issues, and problems around this family of proposals can be identified and need to be considered. Those questions, issues, and problems can in our view be categorized along two dimensions that are structural to define the nature of STEM: an ontological and epistemological dimension dealing with the nature of the scientific knowledge to be taught, and a pragmatic and axiological dimension related to the aims and values of this kind of education.

So-called "integrative" learning processes aim at breaking the disciplinary boundaries in learning, encouraging students to make connections between school subjects.[45] Integrated STEM, although concentrating on the four fields abbreviated in its name, is now attempting cross-curricular integrations that transcend them. As stated before, a high number of different integration perspectives can be recognized in STEM literature; according to Ortiz-Revilla *et al.*,[8] most of these can be classified into two major groups. In the first group, restricted integrations are tested between selected pairs of disciplines (*e.g.*, science and technology, science and mathematics, science and engineering, and so on); in the second group, a more comprehensive integration of content and skills (rather than of disciplines) is sought. A consideration of the epistemological aspects of school disciplinary integration can serve as an organizing tool to understand the apparent (and astounding) variety of integrated STEM education proposals despite their terminological ambiguities.

Strong theoretical dissent and persisting indeterminations in STEM research and innovation create a number of difficulties to bring contextualized teaching to the classrooms going beyond the simple "rumbling together" of conceptual and procedural knowledge of different sources. As a consequence of previous conceptual essays, the available attempts at significantly integrating technology and engineering succumb in front of a traditional, restrictive science- and mathematics-based understandings of STEM.[19,29]

Some irreducible questions therefore come to mind when theoretical and practical aspects of the nature of STEM are reviewed: Can the disciplinary basis in STEM education be defined in a "conventional" way, especially in terms of integration of traditional items of knowledge? How can the integration of STEM disciplines and content items be made more effective in concrete STEM applications?

As suggested in our brief diachronic analysis in the previous sections, STEM emerged with political reasons at its center;[46] the purpose of enhancing the global competitive power of central countries was explicitly put forward in the documentation.[26] Concerns of industrial organizations holding transnational economic power with the loss of workforce in the areas represented in STEM led to their "plea" to the educational system.[31,47,48] While this general situation gets us back to the debates around "ideological" approaches (capitalism and communism) to the structuring of society, labor and education, it raises pertinent questions on the place of STEM in front of the ethical and social components of teaching.

But, can there be a harmonious relationship between the classical political-economic reasons for STEM and the social, cultural, ethical, and humanistic dimensions of compulsory education for all? How can we researchers and teachers help to establish theoretically healthy links? What are the (severe) limitations of STEM's political-economic framing in designing and conducting projects of integrated STEM education?

Answering some of the many questions arising in the two dimensions of analysis that we have defined is seen as a requirement for the effective implementation of STEM practices and for the further development of its foundations. Understanding the nature of STEM requires delving into its most profound aims, examining its political underpinnings, and evaluating the human values that STEM intends to foster. There is therefore a pending question: Why STEM education?[49] That is not completely solved so far. As it is the case with any reform and innovation in education, theoretical, empirical, and practical studies will be indispensable to reveal the conceptual structures that could help us understand the scope and limits of STEM and to elucidate its authentic educational goals.[50]

## REVISITING THE NATURE OF STEM

A valid and licit methodological approach to define the nature of STEM education may be to consider one by one the "natures of" the four disciplines concerned in order to analyze their appropriate epistemological connections. This method is costly, as it requires identifying some key elements of the nature of each school discipline in isolation and then looking for integrations in four theoretical corpora that belong to very different traditions. However, although there are not many educational studies on the "natures of" except for the case of (natural) science,[51,52] emergent theoretical discussion of an envisaged "integrated nature" of STEM already exists.[8] In this and the following sections, yet another approach to this issue will be suggested. Our approach will take into account the paramount importance accorded to the history and philosophy of science in science and mathematics education.[53]

In an integrated nature of STEM, the distinction between its constituent disciplines is an "artifact" of historical, epistemological, or didactical theorisation[54] that can be avoided, seeking for a sum with greater educational value than its parts.[43] We will search for holistic grounds that will free content to be taught from the closed expertise of the established disciplines. Accordingly, and following Sanders,[26] our attempt will immediately recognize that quality STEM education requires more than four letters. Professions, occupations, and activities that resort to knowledge and skills from the fields we are aiming to integrate can open the door to defining the kind of STEM education needed for the near future.[14,15] It is in this context that we state our aims of determining both the nature and the values of STEM in contrast with those from its nuclear areas of science, technology, engineering, and mathematics.

The recent history of science education shows that new "responsibilities" are demanded to school by society. One of these is to educate individuals who will carry out their jobs with a strong bond to science and technology.[55] In the last years, societies sustaining a model of innovation-based development incorporate the rhetoric of the urgent need of relationships between mathematics and science and other more "applied" disciplines in school practices. For us, STEM education requires an even more holistic perspective: It needs to open up to a variety of disciplines and cultural fields.

In the freshest proposals on how to organise STEM, engineering stands out among the four fields and is identified as the key to innovation and integration.[19]

This can be justified in two complementary ways. Firstly, most professional areas that should be supported and enhanced for production-based development and global competition can be considered to belong in the umbrella of engineering, very broadly understood.[56] The skills that should be acquired through education in order to train the necessary human resources mostly correspond to those examined in documentation of university careers in different branches of engineering; problem solving and innovation pervade such policy documents. Secondly, society accords the engineering component salient importance in curriculum documents,[33,39] and this obeys to the political and economic reasons mentioned in this article. "Engineering education" is given more and more place in primary and secondary education;[57] an engineer- and design-oriented integration of content and skills is recommended. It is stated that this new orientation will have benefits in a wide range of areas, from success in science courses in K-12 levels to the development of design abilities, going through the increase in the number of girls and young women attracted to STEM.[58]

Many engineering-design-oriented applications of the STEM education philosophy explicitly include the idea of design thinking: "By definition, integrative STEM education is a pedagogical approach for supporting knowledge construction through student engagement in technological/engineering design-based learning".[59–62]

Design thinking is a powerful theoretical concept that enables the incorporation of strong human and social orientations[8,60] into engineering practices. In many current studies on STEM education, design thinking is included in the panoply of productive skills that are both required and fostered in STEM classroom applications; but despite its theoretical fruitfulness, it is a competence much less studied compared to others.[17] Our poietic STEM model will assume the centrality of design-thinking skills within what we will call the "engineering core". Design thinking in poiesis can also be thought of as a general competence that may be used in a diversity of teaching environments that go beyond the scope of STEM.[63] A poietic conception of design provides theoretical foundations to explicitly orientate productive and creative classroom processes towards disciplinary integrations that are led by humanistic concerns.

Current definitions of integrated STEM education direct students towards engineering and its applications.[64] As Güzey *et al.* state,[65] in this context, the main purpose of STEM should be to train individuals with strong communication skills, who can think systematically and creatively, and who can find appropriate solutions to problems without resigning ethical values. However obstacles are identified: serious technology-oriented integration has not attained sufficient maturity in education so far,[8] and the knowledge and awareness levels of both teachers and students regarding engineering and technology are not at the expected level.[66]

For all the reasons stated in this section, it is necessary for us to take a closer look at engineering as a field of intellectual and material endeavors in order to ascertain its potential to become the main actor in integration processes within STEM.

## SOME ELEMENTS OF THE NATURE OF ENGINEERING

According to Sheppard *et al.*,[67] the engineering profession is customarily understood in three different ways: as problem-solving based on systematic processes; as specific knowledge that affords those processes; and as the sound integration of processes and knowledge. Although a host of definitions of engineering are available in philosophical and technical sources in different languages, an approach that can be useful here consists in identifying commonalities in widely cited characterisations. Accordingly, engineering can be said to be a set of systematic studies that transform the information coming from the results of scientific research into products, processes, systems, structures, and machines to meet the concrete needs of society by using the resources in nature in the most efficient way.[68]

The word engineer is related, *via* its Latin roots, to inventors, designers, constructors and contrivers.[69] In this respect, engineering is characterised by the use of mathematics and science to design for specific purposes. If we go back to philosophical elements in Platonic idealism, engineering would be more importantly concerned with mental design rather than with material design.[70,71] But engineering has two main dimensions: one is mainly mental (rational), while the other is empirical, including testing and experiments. The abstract design is at the basis of the mental dimension; it requires the skills of imagination, creativity, intellectual productivity, and innovation. However, engineering does not end here: after "mentally" designing, processes constituted of complex empirical operations begin. This dimension of "ingeniare" (Latin for imagine and contrive) takes place in two stages: abstract designs are transformed into concrete designs (diagrams, scale models, sketches, maps, *etc.*), and then these become prototype products effected with certain materials and techniques. Relevant scientific information, sophisticated mathematical tools, and a strong basis of current technologies help define the whole process (Figure 2).

Along the cycle of processes depicted in the figure, knowledge used by engineers varies in nature and

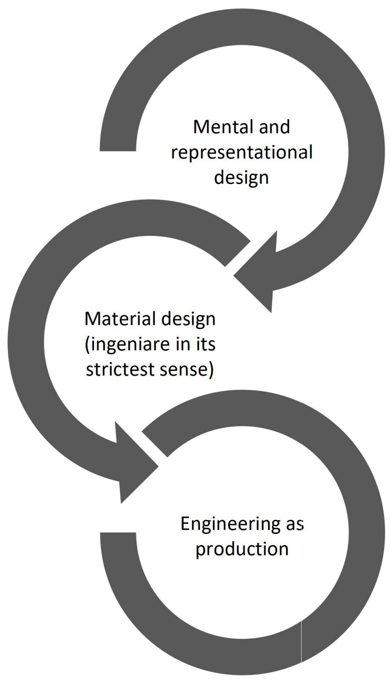


**Figure 2.** Our view of the sequence of processes in engineering.

function. Although the mental dimension includes higher-order psychological competences, scientific modelling provides the template. While mathematics may be manifesting itself more strongly in the step of "representational" design, technology understood as reflective knowledge on how to make (*i.e.*, "techne" + "logia") is instrumental in the emergence of material prototypes and final products. It should be understood here that, even if engineers use existing technologies in their practice, they are at the same time technology producers and manufacturers.[72]

In the case of technology, according to Herschbach,[72] the etymology of the term technology connects it with the Greek "techne", with the meaning of an "art to do" something. The derived term (composed with "logos") refers to systematic applications of an art or a craft that include knowledge of the relevant principles underneath them, as well as the ability to reach appropriate results on the basis of solid criteria. A definition closely following classical studies by Bunge[73] would see it as the transformation of scientific knowledge into products and knowledge-to-do with a kind of engineering ability (including design skills). Engineering is often expressed as an interface between scientific knowledge and technology in the sense of industry-based mass production.[68] Technology literacy, shaped on the basis of engineers' expertise, can be taken as the capacity to understand the principles and strategies required for certain purposes when using, evaluating, and producing technology.[74]

Using this general perspective, it is possible to analyze some of the features that distinguish engineering from both science and technique. The intellectual skills in engineering are not necessarily sought in technicians: innovative capacity and creative thinking are marks of distinction. Techniques are essentially activities tasked with putting the known knowledge into practice in the form of ready-made procedural information and schemas, independent of the processes of emergence of the scientific knowledge they utilize. In opposition, it is expected from an engineer to have a grasp of certain epistemological notions regarding the forms and types of scientific knowledge she or he is using: engineering requires mastery in the application of pertinent items of the scientific corpus.

Engineering literacy as a "threshold competence" in engineering careers is described as the knowledge of mathematics and science acquired through study, experience, and practice in order to develop ways of economically using the materials and forces of nature for the benefit of humanity.[75] This kind of ideas permit to connect engineering with technoscience at the level of school science. Thus, a valued school scientific competence would be to employ scientific and mathematical data and principles with sufficient degree of autonomy and creativity in practical contexts.[76] In addition, engineering is a profession where collaboration is central:[77] studies on the nature of engineering reveal that it requires a "social performance" beyond the technical aspects of problem-solving.[78]

According to Şen,[68] engineering education is many times reduced to the transference to the real world of highly sophisticated technical knowledge that has become the center of its professionality; in his view, the historical and epistemological foundations of engineering have been obscured in educational processes. But any serious attempt at engineering literacy should transcend technification and provide critical guidance to performance. Such guidance could be provided by knowledge from philosophy, logic, argumentation, as well as from aesthetic and ethical concerns.

Taking into account this picture that we have constructed of the nature of engineering, a natural step for us is to consider it the "core" or "center" for a new approach to integrated STEM education (*i.e.*, $E_{STM}$ according to our notation in Table 1). Technology, mathematics, science, as well as other human activities (*e.g.*, arts, culture, philosophy), in our proposal, will firmly integrate themselves to this center.

We think that the theoretical considerations presented here around the nature of engineering as an activity with a strong social dimension position the other basic disciplines (STM) in a key place: they do not become satellites of engineering, but rather shape and channel engineering-design processes. In the poietic conception of STEM that we propose in this article, engineering practices are directed towards design with awareness. Classroom practices in STEM are conceived by us as productive endeavour, but Aristotle's concepts of theoria and praxis have a participation just as fundamental as that of poeisis in our proposal. We will explain how this framework permits an integration of science, mathematics, and technology that neither diminishes their curriculum importance nor blurs their epistemological nature.

At this point, we will look into the history of science for philosophical tools that could have defined adequate grounds for our conception. We consider that the classical Aristotelian triadic characterization of human activity has potential to become a model for our vision on how integrated STEM education practices should be conducted in the classrooms. The engineering center of STEM as the main actor in our play will thus be conceptualized as poiesis.

## RECONSIDERING THE ISSUE OF INTEGRATION UNDER THE LIGHT OF ARISTOTLE'S IDEAS

Aristotle's classical ideas will be here redefined from a perspective interested in their relationship with human and social endeavours, and especially with contemporary academic disciplines. Thus, our proposal will be supported as much as possible in current terminology selected from the educational literature in order to increase comprehensibility.

Aristotle's conception of a person, deployed in works such as *Metaphysics* and *Nicomachean ethics*, describes a complex intellectual system established on a set of relations between the activities performed, the objects sought, the values sustained, and the knowledge acquired. Using these four foci, Aristotle distinguishes three different quadruplets activity-object-value-knowledge (Table 2) and proceeds to a classification of what we now call disciplines moulded on those quadruplets. Interpreting Aristotle's original formulation with the aid of modern scholars,[79–82] we could say that people, through engaging in a particular activity directed towards a particular object and guided by a particular (cardinal) value acquire a particular kind of knowledge. The three canonical Aristotelian activities are named theoria, praxis, and poiesis.

In Aristotle's philosophical system, human beings are characterized as having a natural desire to know about the cosmos. Their attention is thus directed towards phenomena, and they engage in an activity of contemplation that leads to thinking on first principles, this is theoria. Through this first kind of activity, a person moves towards truth, to the obtention of general, universal knowledge of pure causes (episteme), superior in its nature. In the process, she or he acquires sophia, a kind of wisdom with fundaments.

Then, humans want to "make": create and produce concrete products shaping them into "forms" that are useful and beautiful (in a very general sense). In this process of producing, which is poiesis, individuals display techne, a knowledge somewhere in between our contemporary notions of arts and crafts. According to Martin Heidegger,[83] techne entails the anticipation of products and pieces of work as an "art of knowing". Techne leads to the poiesis of products that have universal essence beyond their material and formal concreteness. In turn, Hans-Georg Gadamer's conceptualization of techne[84] assimilates it to a practical art that can be learned (but then also forgotten), where technique (or knowing how) needs to be acquired and exercised and reaches its peak by achieving competent knowledge of what it produces. The activity of poiesis is related to episteme and sophia insofar as it includes planning what will be achieved and developing an original and innovative design.[70,71] The knowledge involved in theoria is both deployed and refined through producing, a platform of poietic knowledge composed of skills related to art and craft emerges.

At the same time, during the process of poietic production, producers' actions and behaviors (their praxis) are deeply changed, since revealing (in Heideggerian terms) the product is a "praxis" action in itself that requires (ethical) critique and reflection. Human productive action is then regarded as good or bad with relative independence of its products.[79] Through making and doing, persons acquire a kind of awareness, a "practical wisdom" called phronesis, partially identifiable with our contemporary notion of prudence. There is no single current term that would today correspond to Greek phronesis. The ideas of reasonableness, prudence, practical wisdom, discernment, or judgment have been used as English equivalents. As a philosopher with a strong background on classical philology, Gadamer chose to translate phronesis into "praktisches Wissen": practical knowledge.[85] Phronesis directs human action towards "virtue" (*i.e.*, aims at ethical, social, and cultural quality, see the works of Argentinian Professor Guariglia),[81] this practical wisdom can therefore be seen as an awareness of the fact that every human action is specific, singular, and contextual and entails consequences. Therefore, poietic activity should always include praxis components of supervision and self-

**Table 2: Modernized interpretation of Aristotle's classification of sciences**

| Activity | Product | Value | Knowledge | Disciplines |
|---|---|---|---|---|
| Theoria | "Contemplative" knowledge of nature | Truth | Sophia | Metaphysics, mathematics, natural philosophy |
| Poiesis | Objects, concrete products | Beauty | Techne | (Applied) arts, techniques, applied sciences (such as medicine and agriculture) |
| Praxis | Action and conduct | Goodness | Phronesis | Ethics, politics |

regulation.

Our vision on the kind of engineering practices that would be central for integrated STEM education can be identified with one of the quadruplets taken from Aristotelian philosophy, given the necessary adaptations. Poiesis, as a synthesis of technique and art applied to practical solutions, seems an adequate idea to metaphorically capture the core of STEM educational practices. Poiesis is an "activity of making" aimed at the obtention of concrete products external to subjects; contemporary Western engineering could, in our opinion, be understood as a poietic activity where theoria and praxis also have substantive participation.

Regardless of the extremely complex issue of whether poiesis can be linked to contemporary technoscience or not, its current equivalents would probably be a variety of product-oriented professions; some of them could be associated to academic disciplines. Any of these two groups of activities would respond to a kind of content that was traditionally disregarded by school curricula.

Practical wisdom can be used as a key idea to subject (school) STEM products, especially when created as works of craft and art, to ethical, political and rhetorical evaluation. Students' production may be useful and aesthetic, but the act of producing in itself may be not ethical in its global purposes and means. In this context, practical wisdom can be understood as a kind of critical competence that assesses the "revealed" products of the project- or problem-based teaching and at the same time allows thinking about the aesthetic, ethical, social, cultural, and humanistic value both of those products obtained and of the acts of producing them. This critical knowledge would be learned through experience in action; it could not be generalized and taught as content.

When viewed from this general framework, and according to our interpretation of the Aristotelian notions, the holistic system of human productive activity, and therefore of school STEM activity as an educational instance, could be modeled as in Figure 3.

Unlike the case with theoria, the common feature of poiesis and praxis are the processes in which an individual's choices and decisions are made effective. But the difference between poietic action and praxic/practical action is that the purpose of the first is a

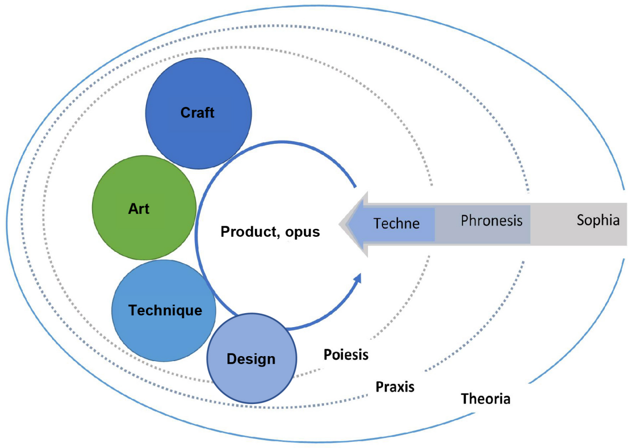


**Figure 3.** Our holistic interpretation of Aristotle's system of human activity.

product outside the individual, in the material world, submitted to the consideration of peers. In practical action, the aim is the abstract act (mainly awareness) that remains within the actor, directed towards them, defined by the action itself. It could be said that verbs are transitive in poiesis while intransitive in praxis: in practical action, human beings "do", while in poietic action they "make".[82] For this reason, poiesis covers all kinds of production-based activities that are driven by the motivation of creating, producing, fabricating, and manufacturing things in general.

If we make an effort to associate our revisiting of Aristotle's system with terminology frequently used in today's educational sciences, Table 3 emerges.

## SCHOOL STEM ACTIVITY AS POIESIS

In Aristotle's original conception, poiesis was inextricably related to the other two human activities that he postulated, as Heidegger argues in his complex writings on the concept of techne. Heidegger's conceptualization of this Greek notion[83] gives emphasis to the fact that poiesis "shows" new truths together with the objects it produces. Hence, techne cannot be restricted to a knowledge that "imitates reality" through human work; it is traversed by theory and values. Poiesis mobilises craft and art for making (*i.e.*, producing products that can be rendered independent of the

**Table 3: Possible relationships between our Aristotelian categories and contemporary educational terminology**

| Activity | Relevant components |
|---|---|
| Theoria: Using scientific concepts and modes of thinking in order to meaningfully understand different dimensions of reality and operate on them | Science and mathematics: models and reasoning<br>Methods and algorithms<br>Explicit treatment of the nature of science and mathematics[51]<br>Technoscientific and informational/computational literacy |
| Poiesis: Solving problems and executing projects that yield as result socially valued products | Skills and competences in tune with those in engineering and technology<br>Production methods and algorithms<br>Design[37]<br>Creativity and motivation |
| Praxis: Reflecting on the nature and consequences of one's own activity while strongly committing to values such as equity and sustainability | Humanistic science education[86]<br>Deep understanding and critical thinking<br>Ethical, social and cultural awareness<br>Metacognition and self-regulation<br>Cognitive, practical, social, and emotional skills[55,87] |

processes of their production), but at the same time needs identifying the underlying principles (theoria) and learning by doing with awareness (praxis).

As it was explained, poiesis as an idealized category to understand contemporary human activity would comprise a wide variety of professions such as architecture, design, decoration, application of digital technologies, and entrepreneurial "invention", among many others. From the philosophical perspective adopted in this article, STEM can be then conceived as STEAM, where the A of course stands for the art-and-craft component, but also wants to capture the inclusion of humanities and social sciences.

The general and universal theoretical knowledge obtained by observing and thinking about nature is used in the process of "revealing" products; this connects school poiesis with the traditional curricular areas of science and mathematics. That same process requires a kind of practical wisdom à la Heidegger in order to achieve individual and collective evaluation of actions. Such "practical evaluation" permits students and teachers to transcend the technical aspects implied in their productions and open the classroom to ethical, cultural, political, and social examination and discussion.

In accordance with the previous considerations, the components of an integrated STE(A)M approach based on Aristotle's ideas would consist of an engineering center (core) surrounded by two shells that enrich it with different types of intellectual tools (content, skills, attitudes, awareness, metadisciplinary knowledge, *etc*.). Considering the philosophical origins of our approach, this "poietic" STEM will be a suitable reference to design and execute a school activity structured around reflective model-based production. It may be interesting to point out here that the modern English adjective "poetic" stands as an alternative form or "poietic". A "poet" is a subject who creates something, not only poems. This term, which is generally used in relation to the art of poetry, essentially refers to all types of artistic and technical creation.[88]

Poietic school STEM practices would propose a teaching directed to the "engineered" solution of real-life problems through resorting to the disciplines of science and mathematics, which provide theoretical principles (*via* models), and of engineering and a variety of technologies, which provide the ability to produce applied products. This engineering-driven problem-solving requires multidisciplinary achievements and a more holistic approach identifiable with competence and literacy, taking ingredients from a variety of school subjects.

The model-theoretical shell and the humanistic shell around the core can conduct the processes of creative knowledge application and of value-laden assessment. Because of the differential introduced by these two shells, productive activity in integrated STEM education can be tailored to the lessons that the teachers deem valuable to teach. STEM teaching, according to our proposal, sets a number of objectives or "achievements" that are productive, creative, theoretical, practical, humanistic, and ethical. Planning teaching can be done in the light of the aims selected by the teacher for a particular group in a particular school year; executing STEM teaching would entail choosing the content and skills that are required for those aims.

Additionally, the humanistic shell can be thought of as the recognition of a "life context", which would gear activity towards valid individual and social goals sanctioned by compulsory education. Using this idea of context-based teaching may open the door towards an honest tackling of the many epistemological and axiological problems of STEM identified in the community.

Poietic STEM understood as a didactical (*i.e.*, teaching) model is constituted (as it can be seen in Figure 3) on the basis of the notion of virtuous and aware action (which could be correlated to behaviour and activity in the now classical constructivist psychology of learning), coupled with processes of accessing and validating knowledge to be used (which would correspond to metacognition and self-regulation in current psychology of learning). Students' actions to "shape" products with a set of recognisable skills require Aristotle's theoretical and practical wisdoms (sophia and phronesis), which, in modern-day terms, would correspond to a coherent interaction between declarative and procedural knowledge.

The process of poiesis can be rephrased from a didactical point of view as follows: students are invited to produce a product (an artifact or a set of ideas) with the externally-driven aim of solving a problem that is chosen in line with their learning needs, interests, and capabilities (the choice is then supported in intellective and motivational considerations). This process includes cognitive, emotional, and social aspects, and results in emerging learning gains that are acquired and consolidated under the form of knowledge, skills, attitudes, values, and metacognitive vigilance. The development of this didactical model of poiesis should then be tightly constrained by our knowledge of students' learning processes, provided by research in the psychology of learning.

If we use current theoretical frameworks of educational theory, poietic STEM teaching is conceived as constructivist, integrative, and humanistic, which in terms of the psychology of learning implies the preference for a sociocognitivist framework.[89] It is this kind of approach that provides the key concepts for our multi-layered conception of poiesis presented in Figure 3 and helps us describe the type of knowledge, skills, and attitudes that we foresee as results. For example, critical thinking, a key component of the rhetoric of humanistic science education, is by essence integrative, insofar it refers to delicate adjustments between theoretical and practical knowledge by means of self-regulation. From this perspective, the ingredients introduced by socioculturally situated knowledge and social-affective skills take us away from the positivistic scientific method and in turn offer a way of acting with engineering skills where design thinking and creativity are essential.

The poiesis approach to STEM, when proposed as a constructivist model, can work in harmony with various didactical methodologies that have been widely demonstrated to have positive results in science and technology education in terms of their fruitfulness to promote students' motivation, understanding, and creativity.[90] Such methodologies include: Involving students as more active participants in their learning process; making learning a meaningful and personal experience with each students' own seal; using context-oriented, student-centered, project-based, participatory and collaborative teaching that focus on students' interests and abilities; including problem solving and critical thinking, artistic and creative activities, integration of different disciplines, laboratory work, and systematic observation.

Didactical poiesis is then here understood as a genuine theoretical model for teaching, rather than as a set of application rules; such model can be adapted to a variety of educational settings, conditions, aims, and curriculum spaces. All these specificities can be incorporated into STEM teaching process as students become acquainted with the proposed contexts of activity. Teachers would then ascertain the nature, extent, and conditions of the processes they will require from them, and the elements to be integrated will be chosen in accordance.

For example, in compulsory science education, our model of poietic STEM can be put into action through enquiry activities, a pedagogy that is consistently recommended for STEM.[91] Enquiry-based teaching embedded in a STEM framework would result in strategies that put children, adolescents, and young people in the place of "amateur" engineers, who want to apply principles from a number of school disciplines to the transformation of a variety of aspects in their daily lives.[92] In this context, it would be recommendable to use exploratory, transformative and evaluative activities.

## SOME IMPLICATIONS OF OUR PROPOSAL

For some time now, the economic model of production-based development guided by global competition between countries has been able to introduce changes in the educational systems so that they provide training more adjusted to the preparation of labor resources. Integrated STEM education has been considered by supporters of this economicist approach a tool that can be tuned to this kind of aims. In the abundant literature around STEM, some problems have been pinpointed in relation with any approach to science and technology education that is heavily based on economic considerations; our proposal of integration of the different STEM fields giving value to the humanist and social dimensions of education would then constitute a step in the right direction towards addressing those problems.

In this article, general philosophy and philosophy of science were used to revisit the nature of STEM and produce a model of integration. Our own approach to this issue was based in proposing engineering as a kind of "attracting nucleus" for the integration of disciplines, content, practices, and values. We have delved into that discipline far beyond the political-economic reasons usually expressed in the argumentation in favor of STEM. In effect, if we start by considering the rhetoric of the documents issued by many countries in this scenario of competitiveness, we can see that an integrated STEM education centered around engineering is located in a solid position. But we want to go beyond this first realization and inspect how an epistemologically sound definition of engineering, which proposes connections between technical practices and art and craft, philosophy, ethics, aesthetics, meta-knowledge, *etc*., can also achieve high coherence with other kinds of rationales, such as the ones found in progressive curricula proclaiming a strong need for citizen education.

In order to achieve this second kind of coupling, we have resorted to a model of school engineering practices shaped on a classical conceptualization of a human activity directed towards producing useful and aesthetic products through ethical processes. Aristotelian poiesis was redefined in contemporary terms so that the human(ist) dimension of productive and creative practices became its constitutive element. A poietic ground was sought that would allow for an integration of epitomic engineering practices (in the very center of the model) and more general educational goals that include elements from Aristotle's theoria and praxis.

The theoretical-argumentative proposal presented here is not to be understood as a STEM application model ready to be used in classroom teaching. This article outlines a philosophical approach from which it is hoped that general teaching frameworks and concrete application instances can be produced (we will mention some steps in this direction at the end of the article). A poietic conception of STEM could contribute to the integration of content, skills and even the ethos of the four STEM fields while smoothly subsuming the kind of STEM practices usually reported in the literature. Entry points to integrating engineering with other disciplines and areas and with the arts are located at the core of the model (the "creative" component). Such core directs school activity towards engineering-design-oriented applications that envisage a valuable opus (piece of work) produced and assessed by students. Our poietic approach to STEM foresees the introduction (from the shells inwards) of skills, understandings, and awareness that are hardly associated with standard STEM proposals. It is for this reason that we strove here for the use of consensual educational terminology that comes from larger and more robust theoretical frameworks (*e.g.*, science education for all, citizen science education, psychology of learning) that have high acceptance in our communities. In this way, the framework that we propose for STEM is able to present the social, cultural, ethical, and humanistic dimensions that we consider have been neglected, in addition to the usual political and economic reasons advocated for in STEM literature. In terms of the specific didactics, this can be done through the inclusion of socioscientific or controversial issues (new energy matrices, global warming, transhumanism, artificial intelligence, coronavirus disease 2019 [COVID-19] vaccination, among many others), where an ethical and democratic framing is unavoidable. The model put forward in this text advocates for a holistic approach to these issues aimed at fostering competencies for the future in today's education, especially through the integration of content and skills in a context of engaged human praxis.

In standard STEM frameworks, students are conceptualized as individuals with physical, cognitive and emotional needs; one major priority in curriculum discourse is to establish ways of educating that take the human being as a whole. In this context, our proposal is adjusted to a multi-faceted understanding of competences: to the classical motor, cognitive and linguistic skills to be developed, it adds the social and emotional dimensions. Additionally, our conception of poietic school STEM practices envisages its incorporation from early childhood education and up to the university level.

Our proposal comprising the core and the two outer shells aims at modeling dynamic relationship between STEM disciplines and further smooth integration of other fields. The so-called STEAM pyramid, proposed by Yakman,[93] is an exemplar conceptualization of multi-layered integration, which we want to adapt as a template to explain our ideas on how integrated STEM education would work (Figure 4). The original pyramid suggests how the contexts chosen by teachers (located at the vertex) can "cement" highly heterogeneous components; among these, we have consistently highlighted design, arts, social sciences, philosophy, and ethics. Our explicit reference to Yakman's model is based on his idea of holistic interaction between fields; in particular, he pleads for a seamless integration of arts. The original pyramid postulates the need of a broad general context for the convergence of the elements, but it does not clearly reveal the actual teaching relationships between those. The status of the different types of items of knowledge, competences, and "literacies" required during integration is also unclear in the STEAM pyramid. Our adaptation in Figure 4 recognizes these difficulties and proposes a more concrete conception of poiesis in context. In it, the extremely different types of performances required by the different disciplinary fields that are integrated can begin to cohere through a carefully planned set of activities articulated from the engineering core.

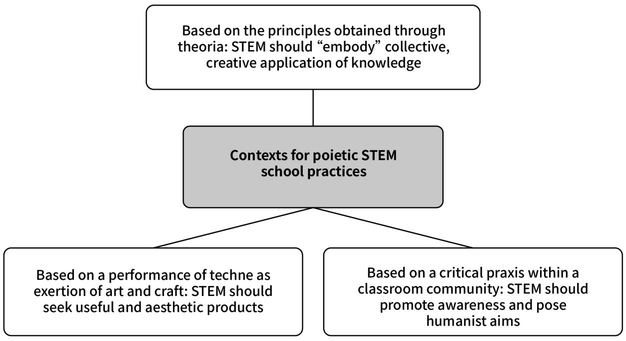


**Figure 4.** "Pyramid" representation of the key features of poietic STEM inspired in Yakman. STEM: Science, Technology, Engineering, and Mathematics.

The philosophical basis of our theoretical proposal strongly supports a functional conception of STEM that recovers many of the values associated to it in the literature and fill some of the identified gaps. In our model, school STEM practices should be aimed at the production of products that are considered useful by a community, since they solve a problem or satisfy a project formulated by them. Our suggestion it then to focus on classroom activities directed to collaborative creation and innovation based on the identification of educational needs.

In our vision, successful applications of integrated STEM education should propose teaching contexts that explicitly include opportunities for students to integratedly explore content and skills from philosophy, logic, culture, and ethics in order to understand, incorporate and exercise universal human values. In consistence with this, since 2021 we have launched a number of research and innovation projects in Turkey and Argentina to implement and assess in secondary school and college classes some poietic STEM activities where the envisaged product has social relevance recognized by the actors. Results of these ongoing applications have not been reported so far. In one of the projects, students design and produce low-cost insulating panels for homeless people.[94] In another, students conceive and execute printed materials where rare human diseases are explained to the general public and to biology and health teachers.[95]

Our rationale is that, in order to further improve the quality of technoscientific literacy, we should move from teaching approaches that use sheer engineering practices reduced to the consecution of technological projects, and rather create complex teaching environments and foment richer classroom interactions where concrete instantiations of the classical virtue of goodness are sought.

In educational systems that envisage more holistic approaches towards citizen literacy for the near future, it is necessary to connect the performance of STEM with rich, responsible social interaction. Based on this requirement, an approximation to the nature of STEM that is centered on an epistemologically sophisticated conception of engineering makes room to fostering shared awareness among practitioners (students of the different educational levels). Beyond science, technology, engineering, and mathematics we need other curriculum areas that help students see that STEM is not restricted to technical processes, but has a more general nature based on the commitment to socially sustained values.

## DECLARATION

### Author Contributions

Sarıtaş D, Özcan H, and Adúriz-Bravo A: Conceptualization, Writing—Original draft, Writing—Review and Editing.

### Ethics Approval

Not applicable.


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### Conflict of Interest

The authors have no conflicts of interest to declare.

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