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A framework for epistemological discussion around an integrated STEM education

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Abstract
In primary and secondary schools, the disciplines encompassed in "STEM" —Science, Technology, Engineering and Mathematics— have usually been studied as separate school subjects, with little effort directed towards non-anecdotal integration. "Integrated STEM education" is one of the most recent interdisciplinary proposals and, under its umbrella, school disciplines are beginning to be integrated in an educationally fruitful way. STEM as a renovated approach is gaining ground nowadays, despite the infancy of its philosophical analysis; explicit epistemological discussion of integrated STEM proposals is either absent or blurred. The overall aim of this paper is therefore to establish an initial framework for philosophical discussion, to help analyse the aims and discourse of integrated STEM education, and consider the implications that adopting any particular epistemological view might have on the aims for general education, and on the construction of science curricula oriented towards citizenship and social justice. We envisage humanist values for integrated STEM education and, after revisiting the currently proposed relationships between the STEM knowledge areas, we adopt a model of a "seamless web" for such relationships that is coherent with those humanist values. A few issues emerging from this model are addressed through the lens of the so-called Family Resemblance Approach, from the field of research on the nature of science, in order to identify some potential central features in a hypothetical "nature of STEM".

Keywords Philosophy of science, Integrated STEM education, Nature of STEM, Family Resemblance Approach, Seamless web, Humanist science education

1 Introduction

The families of disciplines referred to by the acronym STEM —Science, Technology, Engineering and Mathematics— have historically been taught, at the primary and secondary levels, with different levels of emphasis and extension, but always as markedly separate school disciplines. Little effort has been directed towards non-anecdotal, substantive integrations, driven by encompassing educational aims. We could characterize such an approach towards science and technology education using the ideas from Connor and colleagues (2015) of a "simplistic reductionism" in traditional teaching, which would give more relevance to intradisciplinary academic standards than to socially relevant questions and problems.

Disciplinary integration, or interdisciplinarity, has a theoretical background of its own and a fairly broad range of conceptualizations (Chubin *et al.* 1986; Klein 1990; Torres Santomé 1994); although conceptualizing —from a historical point of view— this notion may imply going back in time to philosophers such as Plato. The very concept of *interdiscipline* has mainly been studied during the 20th century, from quite different theoretical perspectives (Frodeman *et al.* 2010). A well-known example would be the ideas of the Austrian philosopher, Karl Raimund Popper (1963), who considered that scientists did not study disciplines but problems, which can in many cases traverse the traditional boundaries of various disciplines. The notion of interdisciplinarity has also been examined in education over the past hundred years or so. For instance, American pedagogue John Dewey (1929) analyzed educational science as a field integrated by various disciplines, aiming at scientifically studying the different aspects of education, understood as a complex social undertaking in several spheres of action.

Taking a renewed interdisciplinary stance, the didactics of science —i.e. science education as an academic field— begins to construct new educational meanings for the acronym STEM, seeking to foster students' literacy in the various constituent disciplines, through more or less extensive integration of the knowledge that arises from them (Bybee 2013). Along these lines, the so-called Next Generation Science Standards (NGSS) created by the National Research Council in the US undoubtedly constitutes an inflexion point for the renewed educational emphasis on interdisciplinarity. In the current literature of science education, we can find several proposals for the integration of some —or all— of the disciplines in STEM. For example, science and mathematics integration continues to be vigorously pursued, at least since the 1930s (McBride and Silverman 1991), and the integration of science and technology has been at the core of numerous humanist proposals for science education during the second half of the last century (Aikenhead 2015)[1]. More modest interactions between the four STEM disciplines —and with other fields such as the history of science, philosophy, or arts— had already been proposed, without using the well-known STEM

[1]The educational objectives of preparing students to understand global challenges and to actively participate in decision-making processes have given raise to several approaches integrating science and technology (S&T), such as science for all; science for citizenship; scientific literacy; S&T literacy; the movement around Socio-Scientific Issues (SSI); education for sustainability; the Science, Technology, Society and Environment (STSE) perspective; and a number of socio-cultural perspectives for science education (see Aikenhead 2015).

nomenclature, with the aim of constructing a broader basis for a more transversal science education at the compulsory levels (Gallagher 1971; Hurd 1975).

"Integrated STEM education" is one of the most recent proposals, and it seems that under its umbrella disciplines are beginning to be combined, put into dialogue and integrated in a more educationally fruitful way. Albeit confronted by some critical voices (see, among others, Chesky and Wolfmeyer 2015; Garibay 2015; Hoeg and Bencze 2017; Zeidler 2016; Zollman 2012), such an approach is expanding nowadays, and there is a significant volume of scientific production on the topic (Brown 2012; Mizell and Brown 2016). In addition, its benefits for student scientific literacy and empowerment, primarily through the application of certain methodologies such as inquiry, engineering design, and project-based learning, are increasingly emphasized in the literature (Bybee 2013; Capraro *et al.* 2013; English and King 2015; Martín-Páez *et al.* 2019; National Research Council [NRC] 2011, 2014; United Nations Educational, Scientific and Cultural Organization [UNESCO] 2017; Wang *et al.* 2011). However, it would be necessary to reflect explicitly upon some *philosophical* issues around the nature of the constituent disciplines and the possibilities for dialogue between them, in order to give substantive meaning to an integrated STEM education. Therefore, the overall aim of this paper is to establish an initial framework *for philosophical discussion*, to help analyse integrated STEM and its aims, discourse and methods, in order to contribute to the task of giving educational rigour and validity to this approach.

The philosophical tools that we will apply for our analytic task were, of course, originally designed to understand scientists' science –and subsidiary, other "disciplined" fields. Accordingly, we will first perform an examination of the STEM disciplines *as they are developed by their professional practitioners*. This philosophical analysis will then be used to extract lessons for the school counterparts of those disciplines, assuming continuities and ruptures between technoscience and "school science".

Critically analysing integrated STEM and establishing some foundational guidelines, to incorporate it into standard science education, will of course need far more elements than only an examination of its philosophical basis. Other disciplines, such as the history and sociology of science, pedagogy and curriculum theory, school policy and economics, and knowledge from non-disciplinary fields and spheres of human activity —equity, ethics, institutional administration, curriculum co-construction, social justice, cultural diversity, management of controversy, etc.— are essential resources. The limits of our proposal in this article are therefore those imposed by our mainly philosophical approach, which cannot fully deal with the complexities of all the interactions of the actors within science education, for instance in terms of interests, worldviews, power, and legitimation.

In the first place, we will examine the "natures of" the four big disciplinary spaces comprised in STEM, in terms of the kinds of intellectual activities that they involve, and of the types of knowledge produced by such activities. For this examination, we will use different contributions from recent and contemporary philosophy of science and technology, seeking to characterize some core epistemic aspects of S, T, E and M.

We will subsequently move to an epistemological analysis of the possible dialogues between such natures, aiming at constructing a web-like depiction that is as coherent as possible. The aim is the eventual construction –via analogical mechanisms between professional practice and interdisciplinary teaching- of an "integrated nature of integrated STEM". Our inspiration for this, of course, is the field of the nature of science in science education, which mainly draws from considerations coming from the philosophy of science of the second half of the 20th century. Our main source will be Gürol Irzik's and Robert Nola's proposal to use Wittgensteinian family resemblances, in order to argue in favour of the "interconnectedness" of our emerging nature of STEM.

Beyond the scope of this essay, further analyses are due on other significant aspects of the foundations of STEM, using the theoretical contributions from other disciplines and from the knowledge possessed by other groups of stakeholders –teachers, students, families, administrators, decision-makers, evaluators, etc.

It is worth stressing that we will here focus on the use of integrated STEM approaches within compulsory education, particularly in primary and lower secondary school, since long-term interest in, and many of the foundations of, STEM competences were established for early childhood education (Australian Council of Learned Academies 2013; Mullis *et al.* 2012).

2 Revisiting the history of integrated STEM education

As a starting point for establishing a framework for philosophical discussion, it is necessary to know the origins, historical evolution, and intellectual lineage of integrated STEM education. Since the historical evolution is described in detail in the literature (see Breiner *et al.* 2012; Bybee 2013; Sanders 2008), we retrieve here only the basic historical events and topics that we deem essential for the subsequent understanding of the philosophical foundations of STEM.

It is often argued that interest in STEM as a major focus of general education may have originated in the 1940s with the prelude to the creation in the US of the National Science Foundation (NSF); such an interest would have accelerated with the launch of Sputnik in the late 1950s. The NSF was created in 1950, materializing the view on scientific progress of Vannevar Bush (1945), the then Director of the Office of Scientific Research and Development. Bush was summoned by President Franklin D. Roosevelt in order to help in configuring the application of scientific knowledge in times of peace (England 1976). As Ramaley and colleagues (2005) stated: “NSF has from its beginning been authorized to initiate and support education programs in all of the fields of science and engineering, at all education levels, beginning with the graduate research fellowship program in the early 1950s” (p. 176). Breiner and colleagues (2012) noted that, from the early 1980s, reports were released showing a strong interest in strengthening science, mathematics, and technology education in the US since early childhood. Such an interest had become apparent by that time; for instance, within the National Science Board (NSB) of the NSF (NSB 1969a, 1969b, 1986). Thus, at the beginning of the 21st century the NSF was described as “the only federal agency with such a broad and comprehensive mission in STEM education” (Ramaley *et al.* 2005, p. 176).

In relation to the origin of the acronym, the NSF, after a series of changes in the letters and the order in which they were included, has consistently been using “STEM” since the 1990s to refer to the curricula for the four disciplinary groups, and later to describe several of its projects for citizen literacy –whether integrated or not. Sanders (2008) underlined that due to the concern of the US that the country might fall behind in global economic competitiveness, STEM-related funding began, and “STEM-mania” emerged.

However, we think it is necessary to qualify this standard historical “narrative”, since the historical evolution of STEM lacks the continuity with which it has usually been narrated. There exist, in this “movement”, discontinuities and reappearances, that is, moments in history in which there was not so much interest in STEM, and other moments in which its emphasis is clearly appreciated. For example, the historical discourse of STEM education forgets the legacy of the STS movement —science-technology-society—. By the end of the 1970s and the beginning of the 1980s, STS perspectives within science education proposed using the interactions between scientific knowledge, its related technologies, and central societal issues as a context for technoscientific literacy (Rip 1979; Spiegel-Rösing and de Solla Price 1977; Ziman 1980). DeBoer (1991) characterizes science-society teaching as “humanistic, value-oriented and relevant to a wide range of personal, societal and environmental concerns” (pp. 178-179). As the STS movement promoted a more holistic view for science education, it was seen as a radical shift from the *status quo* (Aikenhead 2003). STS also shared many features with the education for sustainable development, thus evolving towards what would later be known as STSE, with the addition of the environment (Vesterinen *et al.* 2014). Such a shift in essence also appears in STEM education, in the versions that occupy themselves with sociocultural issues (Zeidler 2016). Nevertheless, the STS movement has several differences with current STEM –which of course includes no specific “S” for society. Among those differences, we can mention their ideological and educational roots, main formative goals, conceptions and methods of integration, and portrayals of the social nature of science.

STS was primarily promoted by post-war scientists who felt they had a responsibility to the public, due to the environmental impact of scientific and technological developments. Also, a root of the movement can be found in the seminal work by C.P. Snow on the “two cultures”, in which he proposed to break the barriers between arts, humanities, and natural and social sciences, “particularly in post-compulsory education” (Ratcliffe 2001, p. 84). In terms of aims, the main original goal of the STS movement was not linked to pursuing scientific vocations, but to bringing the scientific education of university and high school students closer to their needs as critical active members of increasingly technological societies. It is worth stressing that the momentum gained by the STS approach in the 1980s in the UK and US had no long-term impact on mainstream, discipline-based curriculum technicians; it only had a restricted effect on science education through some special projects and programs, with no recognizable influence on traditional technology education (Williams 2011). The main reasons for this may be that innovative curriculum models are difficult to produce; there is little STS instruction in teacher-education programs; and the accumulated research results on the efficacy of STS instruction are inconclusive (McComas 2014). These are lessons to be learnt in the current STEM movement (Williams 2011), despite the much greater effort, and the larger amounts of materials and courses, particularly from private and governmental institutions, from which the STEM movement appears to benefit, in comparison with STS proposals.

In this revisited history of STEM, the Public Understanding of Science (PUS) movement should also be mentioned. With aims close to those of STS, PUS emerged as a movement –and subsequently as a field of studies– in the mid-1980s as a result of the evidence of an extensive “deficit” among the general public in terms of their understanding of scientific knowledge. Initially driven by scientists who adopted this deficit model —it seemed to be enough for scientists to communicate their scientific knowledge, so as to fill the public’s “empty vessels” (Seakins and Hobson 2017, p. 443)— PUS evolved, over the following ten years, into the notion of "public engagement with science", implying a democratization of science, in which research and technologies should be steered with reference to public values (Short 2013).

In standard presentations of the nature and history of STEM education, another important point is also usually omitted: understanding STEM as several school disciplines integrated by the ethos of engineering, which can be understood as "design" and not as the academic discipline *stricto sensu* (Bequette and Bequette 2012; English and King 2015). In fact, this "design-based" meaning for STEM is very much in line with the more recent and interesting STEAM approach —Science, Technology, Engineering, Arts and Mathematics—, especially in compulsory education. For some scholars, such as Quigley and Herro (2016), "the goal of this approach is to prepare students to solve the world's pressing issues through innovation, creativity, critical thinking, effective communication, collaboration, and ultimately new knowledge" (p. 410). In this sense, there are now many voices pointing out that contemporary, design-driven STEAM is more genuinely integrated and balanced than its predecessor (Madden *et al.* 2013; Quigley and Herro 2016).

The fact is that STEM has long been used as a generic label to mention any event, policy, programme, or practice, involving one or more of its constituent disciplines, whether integrated or not (Bybee 2010; Martín-Páez *et al.* 2019); it thus became a familiar overarching acronym. It is only recently that the idea of interdisciplinarity has been more strongly included in STEM; however, the label still has an ambiguous meaning. On the road to disambiguation, several challenges emerge (Bybee 2013): including technology and engineering in STEM's traditional, restrictive conception of science and mathematics; contextualizing problems away from simple knowledge of concepts and procedures; and concreting its precise educational meaning(s). In this context, the concept of *integrative STEM education* or *integrated STEM education* represents the intentional and explicit integration of various disciplines directed towards solving real-world problems (Sanders 2008); such a conception accommodates diverse variants according to the number of integrated disciplines and the way in which the integration is devised and implemented (Bybee 2013).

In the present proliferation of an enormous number of integrated STEM (and STEAM) education programmes, very different epistemological points of view can be recognized underneath each one. Some of them are discussed below.

3 A humanist perspective in the nature of integrated STEM education

Although the main focus of this position paper is to ascertain some epistemological aspects of STEM as a new conception for science education, the analysis of those aspects is inseparable from *axiological* considerations, which are located at the borders of our philosophical approach. We consider that the adoption of certain epistemological views inevitably influences the type of *values* proposed for integrated STEM education and vice versa. For example, the adoption of a position informed by the theoretical ideas of sheer syntactic analysis and strong separation of knowledge from context propounded by logical positivism —the foundational school of the philosophy of science, in the 1920s— does not fit with a humanist view on the active, transformative role of science in a democratic society. Conversely, a depiction of science education as a substantive contribution to collective, critical participation in socio-scientific issues is hardly compatible with the technocratic, elitist, value-neutral tenets of the so-called "received view" of the philosophy of science, which reigned in the Anglo-Saxon academic community after the Second World War up until the 1970s.

For the time being, perhaps the most widely adopted axiological framework on integrated STEM education is the one more or less explicitly chosen by the US in most of its STEM education reform initiatives, which focuses on meeting economic needs, such as preparation for work and high competitiveness. In this sense, several criticisms have been advanced, especially with regard to the "socio-political silence" that is apparent in a lot of STEM policies (Chesky and Wolfmeyer 2015; Gough 2015), which makes it "unlikely [that] students will engage in criticism of STEM processes and practices that support economic growth, and instead will orient students to support them" (Hoeg and Bencze 2017, p. 857). The axiology underlying "orthodox" STEM needs a traditional, *scientistic* epistemology, which deposits faith in the scientific method as a more or less infallible way of producing justified knowledge that can be later applied to an extensive, "aseptic" transformation of the world that, through a linear path, would bring economic development.

Nevertheless, we believe that another theoretical approach to integrated STEM education is possible, based on a more "contextualist" view of the nature of technoscience and laden with more humanist values. Such an approach should include a substantive connection to the social and human implications of science and technology, beyond some superficial considerations on "impact". It should be aimed at student engagement in more active and participatory community-grounded science, including calls for equity, social justice, and full citizenship (Calabrese Barton 2012). So, we envisage an integrated STEM education within a "humanistic" perspective (Aikenhead 2015) that would have the aim of equipping citizens with the tools they need to live in society and to contribute to it, based on the "pillars" of citizen education:

disciplinary knowledge, know-how, substantive comprehension, meta-knowledge, competencies for life and coexistence, competencies for responsible action (Delors 1996). As we said, it is clear to us that only some epistemologies fit with the humanist values that we envisage: we need to retrieve conceptions of science, maths, engineering, computer and information science, and technologies that move away from technocracy and conceptualize disciplines as social organisations, knowledge communities, and cultural legacy.

One big lesson that we learned from the so-called "new philosophy of science" of the 1960s to 1980s is that the heavily scientistic view that dominated meta-scientific reflection in the 19th and the 20th century – and which now seems to be implicit in many STEM proposals- can scarcely capture the complexities of the relationships between science, society, culture, and values. Our proposal is to detach integrated STEM education from its original ideological matrix, which does not contemplate such lessons. This task is possible in the case of many powerful educational ideas; it has already been done with inquiry-based science education and with competencies as innovative curriculum elements, among other topics. The ideological origins of the concept of STEM, in our opinion, would not matter in our educational context; what is essential is that the resulting, re-contextualized, approach is pedagogically powerful and compatible with the current socially proclaimed aims for education. The "philosophies of disciplines" that we want to select for STEM should be directed towards infusing a humanist stance and worldview into science curricula that is compatible with fully engaged citizenship; thus, the epistemological frameworks that we choose should support a science education that prepares students to engage in responsible action towards a more sustainable and just world (Hodson 2006).

Following this line of using educational criteria to select philosophical foundations, two recent schools of the philosophy of science, namely post-Kuhnian philosophy of science and the so-called "semantic view of scientific theories", appear very promising when constructing a "temperate" or "moderate" image of science —and perhaps of its relations with technology and mathematics. Such an image –a "third way" between positivism and relativism- recognizes the extremely relevant achievements of technoscience, without hiding its problems and shortcomings. Post-Kuhnianism and the semantic view could also provide a few elements to help in the conceptualisation of pure and applied mathematics, computation, informatics, engineering, design and technological innovation.

Post-Kuhnian philosophy of science, with its overtly naturalized (i.e., non-normative) approach to the study of the nature of science, provides very robust insights, since it examines "science-in-the-making", especially focusing on epistemological topics such as practices, agents, aims, values, languages, and communities. The semantic view of science, strongly influenced by the linguistic and pragmatic shift in philosophy after World War 2, provides a very detailed and founded characterization of models and modelling that relates to key epistemological issues, such as reasoning, inquiry, argumentation, judgment, and context. We find all these topics necessary for a construction of a prospective "nature of STEM" for science education, promoting the "styles" of thinking and of practice in the different groups participating in the production of science *as a human enterprise* (scientists, technologists, entrepreneurs and inventors, policy-makers, financial supporters, evaluators, users, general public...).

Finally, and along this same line of providing sound foundations for a more humanist perspective for integrated science education, we believe, as previously indicated, that STEAM education appears to be a more balanced option. In particular, the inclusion of arts appears to offer a natural and broader platform for transdisciplinary inquiry and opens the door for sociocultural integration (Zeidler, 2016). It is our contention that any STEM proposal that does not include the contribution of the arts, the transversal focus of design, the drive for authentic disciplinary integration, and a discussion of values "necessarily excludes important areas that inform and contextualize science by grounding them in sociocultural contexts" (Zeidler 2016, p. 17). Nevertheless, in this paper, it is not our intention to present an explication discussion of the epistemology of arts.

4 On the search for an epistemological nature of an integrated STEM education

Is there a "nature of STEM"? This is not the first time this question has been asked (Akerson *et al.* 2018; Peters-Burton 2014), but in the first place it should be acknowledged that such a question is inspired in the study of the "Nature Of Science" (NOS), which is an *educational* construct. From a philosophical point of view, there is no such thing as the nature of science —or of other disciplines—, in the sense that it is very difficult to determine a set of necessary and sufficient traits that can univocally characterize science as a human activity, and that any of the possible characterizations that we can produce are always partial and inevitably theory-laden. Accordingly, the expression "nature of STEM" should be understood metaphorically, just as with NOS: over the last three decades, the community of didactics of science wanted to establish a shared set of "big" ideas with educational value on what science is, in order to teach them to science students —and teachers— within the curricular area of science. According to this perspective, asking the question of the nature of STEM should entail determining the most important characteristics of the different disciplines involved –and of their historical and current relations– *that can be transformed into educational content of formative value*.

Our idea that it is possible to construct an "integrated nature" for integrated STEM education implies resorting to a higher-level conceptualization that goes beyond the sum of the "natures" of the four distinct components in STEM. Thus, we will present in this article an attempt at partially connecting the epistemologies of the STEM constituents into what we will call a "seamless web". Nevertheless, in order to characterize such a web, it is necessary for us to depart from the separate natures of science, technology, engineering, and mathematics. In those natures, we will identify and analyse different epistemological views that, eventually combined through family resemblances between them, will be transferred to the STEM approach as a whole.

As it is well known, the study of NOS, although with controversies, has been extensively addressed (Acevedo Díaz 2008; Authors; Lederman 1992, 2010; McComas 1998). But the same cannot be said with regard to the nature of the rest of the disciplines. Fewer publications have focused on studying the Nature Of Technology (NOT) (American Association for the Advancement of Science [AAAS] 1993; Clough *et al.* 2013). Based on not so many available studies of engineering as a discipline from philosophical, historical, sociological, and pure engineering perspectives, Pleasants and Olson (2019) have recently synthesized key dimensions of the Nature Of Engineering (NOE) for K-12 education. Finally, although the discussion of the philosophy of mathematics and its foundations—loosely identifiable with NOM— comes from ancient times and has ample development (Dossey 1992; Ernest 1992, 1993; Lerman 1990), these issues have not been the subject of as much educational research as that devoted to NOS.

As indicated above, epistemological aspects are often absent in research and innovation studies on integrated STEM education. On the other hand, and although there are different perspectives on the integration of STEM, most proposals have focused on the study of science and mathematics (Bybee 2013; Kelley and Knowles 2016), with less developed and often more inconclusive research on the integration of technology and engineering (Herschbach 2011; Hoachlander and Yanofsky 2011; Williams 2011), as these disciplines are not usually explicitly present in compulsory education (NRC 2011). It has evident repercussions on the possibility of deepening the epistemological analyses. The most prominent disciplinary field analysed from this "nature-of" point of view is undoubtedly science —i.e. the natural sciences—, with the epistemological aspects belonging to the rest of disciplines, up until now, mostly ignored in educational literature. Chesky and Wolfmeyer (2015) are among the very few authors that discuss those aspects in depth, mainly addressing mathematics and science, and the relationship of both disciplines with technology. In summary, a deeper analysis of review studies on integrated STEM education shows that STEM's epistemological issues are overlooked, veiled due to the complexity of their disciplinary relationships. We will select here some salient epistemological features from each of the four integral disciplinary fields.

In the case of NOS, academic production is overwhelmingly abundant. For almost three decades now, the didactics of science has, from a variety of philosophical perspectives, analysed science as a process and as a product, and has produced "key ideas" on its nature that are suitable for teaching in the science classes. There is nevertheless an emerging consensus that integrating more "meta-scientific" perspectives is needed in a new approach, in order to convey a more educationally valuable depiction of the scientific enterprise (Erduran 2014).

Establishing some key points for an educational Nature Of Mathematics (NOM) is almost an insurmountable task, given the perplexing diversity of –often contradictory- epistemological depictions of the discipline produced since Antiquity. Located within an integrated STEM framework, Chesky and Wolfmeyer (2015) stated that, for NOM, it is important to conceptualize numbers and other mathematical entities as relationships that do not exist *per se*, but rather as —cultural— constructs that frame our possible ways of seeing the world, thereby excluding alternative conceptions of reality (Warnick and Stemhagen 2007).

Before we can begin to talk of the Nature Of Engineering (NOE), it would be necessary to have a definition of what engineering is. But there is no single accepted definition in the literature of engineering education or of the philosophy of engineering. Nor is there even consensus on the centrality of *design* within engineering: design-oriented conceptions of engineering exist —as opposed to modelling this discipline after the natural sciences—, especially since the 1960s, but Houkes (2009) remarked that those conceptions are typically counter-movements instead of a new orthodoxy, if the curricular structure of engineering schools is analysed in most countries. Nevertheless, although acknowledging that engineering involves much more than just design, several science-education authors have considered design as a central feature of NOE, because of its prominence in the academic literature and in educational settings (Pleasants and Olson 2019). Another central feature of NOE that has been proposed in recent science-education papers, which resort to post-Kuhnian views, is that any engineering production design must attend to both the internal workings of a technology and its function in a social environment. Engineering translates “ill-defined goals” into specifications that can be used to guide design work, while taking into account design constraints —safety, reliability, costs, sustainability, etc.— that limit the possible solutions and should have to be socially negotiated (Antink-Meyer and Brown 2019; Pleasants and Olson 2019). While constraints demonstrate how engineering is shaped, it is worth stressing that not all of them can be overcome, since some problems are simply not technological in their nature (Waight and Abd-El-Khalick 2012).

Despite its relevance for citizenship, technological literacy and NOT have received insufficient attention in science education (Pleasants *et al.* 2019). Indeed, a study among leaders of professional organisations representing science, engineering and mathematics concluded that there is no consensus on the perception of what “technological literacy” should entail (Rose 2007). Educational discourse around science teaching tends to show naïf or outdated ideas about technology; arguments underlying STEM are not an exception to this tendency. They usually present technology under an instrumental conception, which aligns it with “applied” scientific research and values it only for its role in solving concrete human needs (Waight and Abd-El-Khalick 2012). Nevertheless, over the past few years, this view has begun to be questioned. Waight and Abd-El-Khalick (2012) described five dimensions that need to be considered for NOT, associated with perspectives from contemporary philosophy of technology: technological progress, technology as part of systems, technology as a “fixed” variable in the system, the cultural context of technology, and the role of values, expertise, innovation, creativity, and invention. Pleasants *et al.* (2019), based on an extensive analysis of philosophical writings on technology, showed some issues, organized by different levels of relevance for personal and societal decision-making, that should be included when dealing with NOT in a more thoughtful and ethical STEM education.

A philosophical problem in the construction of NOT and NOE is that technology and engineering cannot be identified exclusively in terms of the existence of an independent body of systematic knowledge with academic autonomy (Meijiers 2009), nor in terms of their own methodologies (Mitcham and Schatzberg 2009). As Meijers (2009) highlighted:

> technology or engineering is primarily a practice which is knowledge-based. In this practice scientific knowledge, but also experience-based know-how, codes and standards, customer requirements, organizational, legal and economic constraints, physical circumstances, scarcity of resources, uncertainty and ignorance play an important role. (p. 3)

So, a strictly methodological demarcation among applied science, engineering, technology, design and innovation is clearly insufficient to produce ideas with educational value and to seek for fruitful integration between these fields. Both NOT and NOE both need more contextual, value-laden views.

5 A model of “seamless web” for understanding the knowledge and practice in STEM disciplines

Is it possible to educationally address the nature of STEM (NOSTEM) as just the sum of the natures of the four constituent fields (NOS, NOT, NOE and NOM)? According to our portrayal of a STEM education aimed at enabling students to solve relevant problems in their adult lives, the answer is clearly no. Then, we first need to identify similarities and differences in these types of knowledge and practice that we can discuss at school, and only afterwards can we identify emergent ideas from their combination and integration that will be useful for a humanistic science teaching. We are aiming at a NOSTEM that is appropriate for citizen education.

Antink-Meyer and Brown (2019), based on a review on the literature of philosophy of science and engineering and science education, describe the primary distinction between engineering and science as teleological –residing on objectives and finalities. Using Vincenti’s words (as cited in Antink-Meyer and Brown 2019): there is a “fundamental difference between engineering as the creation of artifacts and science as the pursuit of understanding” (p. 541). This is an example of what Houkes (2009) calls the “truth vs. usefulness” intuition: scientific knowledge aims at finding out “true” —i.e. valid— theories, while engineering knowledge aims at practical usefulness —an intuition that conflicts with a strictly instrumental view of science, cultivated by positivistic philosophies of science, but that is also too schematic for epistemological analyses in the “historicist turn”. Among other authors, as Stephen Toulmin (1972) has noted, the basic focus of scientific research after World War 2 was no longer nature itself, but some “unit” of engineered artefacts, such as a reactor, a missile, or a computer.

In a similar way, many authors have sought to study the differences between science and technology in strictly axiological terms, showing that they mainly differ in their aims, values and actions. According to this approach, the central goals of science would be epistemic, i.e., the creation of knowledge that explains, while the aim of technology could be depicted as the construction of things or processes with some socially useful function. These distinctions are anchored in Mario Bunge’s idea of technology as applied science, which is called the "linear model" of the relationship between science and technology. Such a theoretical framework is widely spread among the general public, shared by many stakeholders, and is a common misconception in science classes, but it is frontally questioned in studies on the philosophy of technology and engineering.

Regarding the differences between technological and engineering knowledge, it has been argued that engineers are more involved with applied scientific knowledge and technologists focus more on the actual construction and operation (Mitcham 1994), but current practices in technology appear to blur this distinction. Although historically some technologies were developed via trial-and-error —for example, the use of active principles for medical treatments—, or slowly and iteratively modified through the work of skilled artisans and craftspeople —for example, the bicycle—, modern technological development differs from these previous modes, due to its close relationship with scientific knowledge (Kroes 2012; Marcus 1996).

Several scholars argued that considering science, technology and engineering as separate epistemological practices will never be sufficient to take into account the richness and variety of actual scientific and technological developments, since designing and constructing material things or processes are also frequent activities in science (Radder 2009; Tala 2009). Not only as Latour (1987) and other post-Kuhnian authors that support the notion of technoscience point out, but scientists, engineers and technologists are also centrally involved in practical processes of intervention, negotiation and construction –in the course of the 20th century, science has increasingly become "big science", requiring the formats of an industrial organisation. Large, multinational research groups are involved with scientific design and testing of experimental machines, accelerators and detectors (see, for example, Galison 1997). Scientists, including mathematicians, use sophisticated technology to produce models, to perform experiments, to manipulate and store data, to write research papers, and to communicate with other scientists.

Finally, theoretical physics, chemistry and biology, parts of engineering and many other academic fields overlap with applied mathematics. Not only discrete mathematics, statistics, computational science and data science are key for the current development of all scientific, technological and engineering endeavours, but also mathematics is, in turn, affected by technology, with computers that are used in "experimental mathematics" to justify mathematical claims and to produce brute calculation for suggesting or testing general claims (Avigad 2008).

So, how can the relationships between science, technology, engineering and mathematics be addressed? The models proposed by social scientists on the "nature" of those relationships can be divided into three groups (Radder 2009, pp. 24-25):

a) Primacy models, in which some kind of primacy —empirical, conceptual or evaluative— is given to one of the areas. The "humanities tradition" in the philosophy of technology is used to emphasize the practical basis of engineering and science, giving primacy to technology, while the engineering tradition, stressing the scientific basis of engineering and technology, will be inclined to assign primacy to science.

b) Two-way interactive models, which assume that technology, engineering and science are independent, yet interacting, entities.

c) Models assuming a "seamless web" between technology, engineering and science, which means that these activities are so strongly intertwined that they cannot be sensibly distinguished in action.

These latter models consider that science, technology and engineering form part of a seamless web of society, politics and economics. As stated by Hughes (1986, p. 282): "Heterogeneous professionals -such as engineers, scientists, and managers- and heterogeneous organizations -such as manufacturing firms, utilities, and banks- become interacting entities in systems, or networks". Hughes proposed several examples of webs, both at the individual and at the social level. For example, the seamless web of thoughts of Thomas Edison as expressed in his notebooks, where mixed topics commonly labelled "economic", "technical" and "scientific" appear. Another example is the improvement of the public health system in late 19th-century Germany where no clear distinctions may be established between the goals and means of scientists, academics, engineers, educational and state ministers, and their organisations. This case shows scientific knowledge integrating a seamless web that joins social, political, ideological, and design dimensions along with the conceptual content of science (Hughes 1986, p. 289).

Because of the claimed seamlessness between the interacting elements, proponents of such models often use the post-Kuhnian notion of technoscience in all its theoretical meaning, and so, sociological, technoscientific, and economic analyses are permanently interwoven into a highly coherent web. These models capture most modern technological and scientific practices more accurately, especially in the era of big science —see, among many others, the analyses by Haraway (1997) or Latour (1987).

Given the educational aims of STEM that we envisage, centred on contributing to a general science education for all and to the preparation of informed citizens, we consider that an integrated STEM approach for primary and lower secondary science should adhere to a "seamless-web" understanding of the relationships between science, technology and engineering, and also include mathematics. The web, as we suggested, would also reach to the socio-political context. Such systemic understanding seems to be appropriate to anchor a useful NOSTEM for compulsory education.

6 A possible philosophical framework for integrated STEM education: the "family resemblance approach"

In an effort to determine a philosophical framework for NOS that is capable of transmitting the richness and dynamicity of science, Irzik and Nola (2011) adopted Wittgenstein's family resemblance approach (FRA), considering the different natural sciences as cultural entities in a "family" with many shared characteristics that are similar across sciences, as well as other specific traits that make each science unique. The FRA can then accommodate both the domain-general and the domain-specific features of science, assuming, as we pointed out above, that it is not possible to determine a set of necessary and sufficient conditions for defining science.

Following Irzik and Nola, science can be understood as a cognitive and social system whose investigative activities have a number of aims achieved with the help of methodologies and methodological rules, and systems of knowledge certification, and dissemination. These elements are in line with institutional, social, and ethical norms. When the alignment is successful, science "ultimately produces knowledge and serves society" (Irzik and Nola 2014, p. 1014). In our view, this framework is extremely appropriate as a basis for sketching out what an epistemology of integrated STEM, understanding the label as a seamless web of disciplines, would look like. We are briefly presenting some of the epistemic features that could characterize such a NOSTEM, features that are not stressed much in the scarce literature on epistemological issues within integrated science education. We will bear in mind the dimensions proposed by Irzik and Nola (2014) and our humanist approach to STEM, aiming at an education for all.

Related to the aims and the values of integrated knowledge production in a seamless web of disciplines, the ultimate goal of the disciplines constituting the web of STEM should be the responsible resolution of relevant societal problems within a sustainability matrix. Such an idea would be within the core of the family resemblance between science, technology, mathematics, and engineering. Each of these four constituents, in their turn, would have their own separate goals —the development of solutions, the understanding of nature, the production of machines, the design of processes, etc.—, and any such goals could be discussed with students for their integral literacy.

Related to methods, integrated STEM education should stress that nowadays the frontiers between areas are blurred in the seamless web of STEM practices, a point that is not usually highlighted. For example, as Radder (2009) argued, scientific practices include "the regular application of a variety of rules of thumb and intuitive models for solving (…) problems, the making of approximations based on mathematical or computational feasibility and the black-boxing of (parts of) systems through tuning to experimentally determined parameters" (p. 73). All these features can for example be seen in scientific simulations. When transforming mathematical models into discrete algorithms that imitate the behaviour of systems, scientists should take into account the computational cost of the resulting algorithm, as well as the possibility of that algorithm being unstable, and thus producing unreliable results. In those situations, they need to simplify the model by ignoring or discarding some factors, by reducing the model's degrees of freedom, by adopting what are known to be rather unrealistic assumptions of symmetry, by including mathematically simple relations with no direct connection to the original differential equations, or by substituting the real physics of a process, which might be overly complex, with phenomenological relations. In short, the "parametric" relations that appear in a simulation often have no direct counterpart —in a strictly realistic sense, from a naïve realist point of view— in a real system (Authors). However, these procedures have for a long time been attributed to technology rather than to science, in the view of several scholars such as Bunge.

Modelling, the most relevant characteristic of the scientific mode of knowledge production according to the semantic view of science, is used in engineering in a number of forms —conceptual, analytical, numerical, physical…— as a means of gathering and organising data and collecting feedback (Pirtle 2010). In the engineering sciences, modelling is a strategy for understanding, predicting, and optimising the behaviour of devices or the properties of materials —real or possible. In technology, modelling is usually used to represent the design of a device or its functioning (Boon and Knuuttila 2009).

On the other hand, within this framework that understands STEM as a seamless web, experimentation and design have attracted increased attention (Tala 2009), because during these activities the world is simultaneously written and read technologically in two senses: some of the phenomena are instrumentally revealed, while increasingly more phenomena "are technologically produced and tailored" (Tala 2009, p. 283). Scientific knowledge is not simply "discovered" from nature, but constructed through careful and well-planned experimentation and the accompanying interpretation of the experiments. So, when experimentation is addressed, scientists and engineers alike rely on scientific design, which in the same way as engineering design, aims at the control of material laboratory phenomena and its manipulation, as a basis for successful outcomes (Tala 2009). In particular, technoscientific research is full of tools "to make something happen", which belong to a specific style of laboratory experiments aimed at manipulating objects and properties (Hacking 1983); therefore, scientific research cannot be reduced to just testing hypotheses or representing nature (Vincent and Loeve 2018). Thus, design is not an exclusive feature of engineering. Furthermore, as Vicent and Loeve (2018) stressed, "where knowing and making are intermingled, nature itself comes to be viewed as a designer" (p. 176). Design is then the ideal type of research of technoscience, which may still co-exist with the traditional modes of observation and experimentation. Some branches of mathematics are also using today an experimental methodology, based on computational methods for obtaining, verifying, and extending knowledge; suggesting theorems and making conjectures plausible; and providing insights and understandings (Avigad 2008; Borwein and Bailey 2004).

Addressing the issue of the kinds of knowledge produced by the STEM disciplines, it could be interesting to highlight three candidates to family resemblances. First, designing functional objects and organisms is an end in itself rather than a means toward an end (Vincent and Loeve 2018). Second, people involved in technoscience —scientists, engineers, technologists— consider that a proof-of-principle constitutes a genuine and valuable instance of knowledge-production. Such knowledge, from the point of view of the traditional conceptions of engineering, was seen as temporary and limited, calling for further research-and-development efforts in order to be scaled-up (Vincent and Loeve 2018). Third, within the seamless-web metaphor, innovation is also valuable knowledge —a point which is addressed below.

The FRA model includes a dimension of practice, dealing with the set of epistemic and cognitive practices that lead to consolidating knowledge, processes and products. In the case of technology, there would be specific practices to attain the closure and stabilisation of a particular technology, strongly resembling the consensus reached in science after alternative interpretations of a phenomenon are discussed. Pinch and Bijker (2012) defined "closure" as the emerging consensus when considering that the problem motivating the development of a technology has been solved. Closure is more complex in engineering and technology than in science, since the variety of groups involved with both the production —that is, in the definition of the problem— and the ratification of technologies is greater —among them, individual inventors, scientists, design and production engineers, firms or state agencies, consumers, sales and marketing teams, financial advisers, lawyers, politicians… In addition, although a solution can be reached, many more problems emerge —some of them beyond the tractability of the original problem— as the technology is developed and expanded to other contexts (Hughes 2012; Volti 2014). Thus, unlike in science or mathematics, in technology different groups may define the problem and success or failure in different ways. Despite these differences, the family resemblance holds, insofar as, in the case of science, "nature is never used as the final arbiter since no one knows what she is and says" (Latour 1987, p. 97).

Other issue around practices in the STEM disciplines have to do with the processes of *validation*, which appear to be more or less clear in science (although at present simulations are disputing our traditional understanding of validation, Authors), but have not been as thoroughly studied in engineering science, in which it is plausibly related to practical usefulness (Houkes 2009).

One striking difference between scientific, engineering and technological knowledge is around the dissemination of results. One of the classical, implicit norms in science is that scientists cannot claim ownership of knowledge and they have to communicate their results transparently, so that the way in which they were achieved can be replicated (Merton 1973). It happens quite differently in the world of engineering and technology, where the "degree of expression (or codification) of technological knowledge may be largely due to socio-economic circumstances" (Houkes 2009, p. 336).

Related with ethics, when aiming at a humanistic perspective for STEM education, it is necessary to address several features. Among them, profitability. As Pleasants and colleagues (2019) highlight, "technologies exist in an economic context, which means that profitability is often an end that is actively pursued during technological development, sometimes at the expense of the other goals" (p. 579). Also, technology and engineering shift from the classical image of science as a value-free enterprise: technoscientific products of knowledge are explicitly value-laden —of epistemic, economic, socio-political and ethical values (Vicent and Loeve 2018). Values are frequently in conflict, demanding assessment and regulation.

On the issue of social values, a common feature of all disciplines within STEM is that they are affected by and they affect cultural norms and societal needs. Moving away from commonplace extreme positions related to the influence of technology in the changes in society (either that technology determines changes or that humans freely direct technological development, see Pleasants *et al.* 2019), a NOSTEM should seek a temperate position, grounded on moderate realism and rationalism. Such a position considers that technological systems are both socially constructed and society constructing (Hughes 2012). That is, new technologies developed in —and shaped by— a particular social context make possible certain types of social changes, which can be positive, negative or neutral.

We consider that, in the social category of analysis, the notion of responsible research and innovation should be included. Innovation is a key element in the seamless web, and an inherent characteristic of the activities that are performed in science, technology, engineering and mathematics. It is worth noting that the very concept of innovation —what innovation is, how it works and what its implications are—, a universal topic in official reports and recommendations, remains fuzzy, not only in science and technology education, but also for general audiences. Developing an epistemological understanding of the ideas of technology and innovation as part of human evolution is a pre-requisite for educating students to overcome simplistic and widespread assumptions about the relationship of those ideas with science —i.e. science as the driving force of progress, technological determinism, innovation as something essentially good, etc. (Authors). This kind of philosophical discussion is also needed, in order to challenge selective and biased "histories" of specific technologies that ignore the impact of structural, social, economic, political, and psychological adjustments that were necessary to support their implementation (Volti 2014). Integrated STEM education opens an opportunity to debate these aspects for developing genuinely responsible literacy aiming at sustainability.

The features of the last categories of the FRA model are much less defined in the literature. In the dimension of the social organisation and interactions, we might address the characteristics of big science and the different structures that are being proposed, as well as the recent trend in citizen science —or "crowd science"— and the growth of user-driven and user-led innovation. In these contexts, citizens may co-create scientific and technological knowledge or actively participate as innovators for the development of new products and services (von Hippel 2005). Finally, NOSTEM should address the underlying financial dimensions, including the ways in which the ethical, social and political configuration of economy shapes the seamless web of STEM (Birch 2013).

Following an example constructed by Kaya and Erduran (2016), Table 1 synthetizes the features that we have compared from a family resemblance approach for our proposal for NOSTEM.

Table 1: Some features in an FRA model for NOSTEM

Seamless web of the four STEM constituents as a cognitive-epistemic system	**Some epistemological features that might be addressed**
Aims and values	The responsible resolution of relevant societal problems within a sustainability matrix
Methods	Many shared methodologies —experimentation, modelling, design— Design as a central methodology in technoscientific research
Knowledge produced	Design of functional objects and organisms Proof-of-principle Innovation
Practices	Closure Validation
Seamless web of the four STEM constituents as a social-institutional system	
Social certification and dissemination	Scientists and mathematicians cannot in principle claim ownership of knowledge The degree of expression —or codification— of technological knowledge may be largely due to socio-economic circumstances
Scientific ethos	Products of knowledge are explicitly value-laden —with epistemic, economic, socio-political, and ethical values Values are frequently in conflict and demand assessment and regulation
Social values	Technological systems are both socially constructed and society shaping Sustainability and responsible research and innovation
Social organisations and interactions	Big science Crowd science
Financial systems	The ethical, social and political configuration of economy configures and shapes the seamless web

The features that we have reviewed here, as well as many others that would emerge from now on, cannot and must not be reduced to a set of declarative statements for teaching; rather, they should constitute "themes" to become engaged with and to elaborate upon (Matthews 2012). It is worth stressing that, from the humanistic perspective, we envisage an understanding in integrated STEM education that science, technology, engineering and mathematics are inextricably intertwined and form part of a seamless web of society where politics and economics constitute a central element for preparing young students to engage in responsible action towards a more sustainable and just world. Students will be decision-makers in socio-scientific topics and producers/consumers of new information, knowledge, and technologies. For example, when addressing the problem of the use of plastics, a typical STEM problem, young students may be able to understand the deep connections between chemistry concepts, engineering processes, and technological products as part of the cognitive-epistemic system; such connections are very powerful for producing new knowledge, products, and discourses. But students should also direct their attention towards how STEM disciplines, seen as a social-institutional system, are embedded in a larger socio-economic matrix that may differ at regional and global levels. As a result, students may become able to decide on the actions, for example, with regard to plastics, that should be taken in their contexts. We consider that all these understandings cannot be achieved, if the "natures of" S, T, E and M are separately addressed at school.

Also, the humanist approach to STEM implies assuming from the very beginning that STEM-derived knowledge is one among many other ways of knowing (Chesky and Wolfmeyer 2015), but at the same time recognizing that, in our Western societies, a poor understanding of the conceptual products of STEM will certainly be detrimental for the exercise of full citizenship.

The adoption of an *integrated* epistemological framework for STEM curricula, teaching and materials, constructed highlighting the family resemblances between the four constituent groups of disciplines, does not imply neglecting the specific features of each type of knowledge for teaching. Following the example given by Williams (2011), the relevance of the technological knowledge needed for solving a problem is defined by the very nature of the problem, because the pursuit of the solution determines the information that is needed. The knowledge needed to solve an engineering problem is somehow pre-defined by the context —electrical, chemical, organisational, sanitary, etc.— and so, it is not as dependent on the nature of the design problem. Technology contexts are less associated with a defined body of knowledge than engineering; accordingly, if we for example "enter" a STEM project through engineering, students will have less space to explore "new", "creative" knowledge and work towards its definition.

7 As a conclusion

When approaching STEM as an emerging construct that is gaining momentum in our academic community, meta-analyses, theoretical studies, sound argumentation, and critical reflection from philosophy are necessary, since all of these offer a better conceptual comprehension and a deeper understanding of the scope of STEM empirical research and practical proposals and their limits. Conceptual approaches to the discussion of STEM help locate it within the framework of a consensually established set of humanist aims for meaningful education (Gil Cantero and Reyero 2014).

The available philosophical views on integrated STEM education are still very incipient, with most of its epistemological aspects absent or blurred. We must discuss these issues without reluctance, in order for STEM to develop as a valid pedagogy. In this paper, we have stated that renewed approaches to science education should pursue the integral education of people with the aim of achieving full citizenship, and that this educational process should be done from very early stages. Thus, integrated STEM education should remain committed to what we have called a humanist approach, identified with sound reasoning, argumentation, criticism, participation and responsible action (Zeidler and Sadler 2007). If every epistemological stance has an underlying axiology, we think that it is relevant to adjust our philosophical position to these educational aims that society currently supports; it could be seen as the construction of an *ad-hoc epistemology for school science*, using a careful selection of contributions from the philosophy of the disciplines and from other "meta-theoretical" efforts.

On the basis of a rapid reflection on the diversity of philosophical views in the late 20th century and of axiological considerations, we have sought, in this paper, to move away from a technocratic and economy-driven perspective on STEM, which highlights intra-national economic and utilitarian intentions as much as it reveres technological supremacy (Clough *et al.* 2013). Such a perspective was behind the creation of the acronym and is still perpetuated in many educational settings.

After revisiting, from an epistemological point of view, the current relationships between the knowledge produced in science, technology, engineering and mathematics, we adopted a "seamless web" model for these relationships, which appears to be coherent with the educational aims that we envisage for STEM. Issues emerging from our view on STEM were addressed through the lens of the FRA approach proposed for NOS, in order to obtain some potential features for a prospective NOSTEM. We would like to note that, as powerful as the "seamless web" perspective may be —both at the analytic and the educational levels— it disregards the fact that professional STEM disciplines are strongly separated at an institutional level. Nevertheless, the idea of a "seamless web", as introduced in the context of this paper, is intended to transcend this difficulty, since it refers to the coordinated work of the natures of the different disciplines *in school science*.

Advocating the adoption of a particular set of epistemological views will undoubtedly shape such issues as relevant as the construction of national and local curricula and the choice of classroom pedagogies. In the same way, the epistemological assumptions that we make can have a direct impact on the way knowledge is transmitted and, therefore, on the construction of knowledge by students and on their ways of understanding the world and acting within it. Therefore, within an inclusive and equitable perspective for STEM education, it is important to introduce epistemic "heterogeneity" into our pragmatic approach, given that knowledge systems, including science, are not objective or "natural", but socially and ideologically constructed (Harding 1991). Such pragmatism in the choice of epistemologies should of course be done in a way that seeks coherence with our proclaimed aims and values and avoids philosophical contradiction or inconsistency. An example in this direction of selecting appropriate epistemological foundations would be to resort to the work on "engineering for sustainable communities", developed by Tan and colleagues (2019), which would imply expanding the epistemological constructs that we use for STEM far beyond the more "canonical" epistemologies that were used in this paper.

We have presented here our –still very tentative– framework as a way to conceptualize a STEM education of highly formative value and as a basis to construct integrated proposals aiming at ambitious educational objectives. However, such a framework might also prove to be a way to *assess* the quality and extent of integration among the four STEM academic fields in STEM education proposals[2]: it might help us recognize when curriculum, instruction and evaluation show authentic *theoretical*, *methodological* and *axiological* integration in a thoroughly transversal manner that co-ordinately directs S, T, E and M towards the "bigger" purpose of cognitively and socially relevant problem-solving.

A humanist approach to science education, as discussed here, would not focus on the development of scientific vocations, but these will naturally arise, a point that has already been detected (Maltese and Tai 2010). It is our contention that an educational approach should not be subordinated to economic directions, but should rather aim at developing the range of skills necessary for students to achieve full citizenship in the society in which they live (UNESCO 2016). Integrated STEM curriculum and teaching should put social and cultural meaning first, aiming at social justice through a more holistic technoscientific literacy. Thus, the intention of this paper has been to contribute with a few initial elements to an understanding of the implications that adopting one or another epistemological view on the four STEM disciplinary fields and on their integration can have on general educational for all and on the construction of future society as a whole.

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Response to Reviewer 1

Reviewer's comment:
I have to share I was very off put by the exaggerated claims contained in the abstract that the STEM disciplines have "long been studied from a mono disciplinary paradigm." The authors should recognize how dramatically this contrasts with how scientists are traditionally trained and also how disciplinary sciences are taught. Biologists take many courses both as undergraduates and graduate students outside of their specific focus of study, and by this I mean not only that ecologists take evolutionary biology courses, but also physics and chemistry courses. As someone who has a graduate degree in biology and teaches biology on a regular basis, I often find I need to refresh students on basic chemistry and physics. One could take the claim they are making as suggesting philosophers of science often myopically focus on examples from their own areas of science expertise, and this certainly a fair claim. But even here one should recognize that for decades philosophy of science was dominated by individuals trained in physics, and as a consequence, the focus of much philosophical inquiry in the 1930s onwards has been that of drawing attention to features of biology, chemistry and geology that do not fit neatly into philosophical models that myopically focus on examples from physics. In short, I don't buy the central assumption that appears to lie behind the entire paper.

Authors' response:
The claim of the existence of a "mono-disciplinary" approach to science education was formulated in relation to school science, especially at the secondary level, where students follow courses on separate sciences (physics, chemistry, biology, and eventually geology and other natural sciences), but with little interaction either between them or with mathematics and technology. As the reviewer points out in the comment on NGSS, it is only recently that problem- and project-based approaches are returning to the incorporation of more genuine multi- or interdisciplinary approaches within the science classroom. We have now clarified that point in the abstract and in the rest of the text. The abstract as a whole has been modified and the first two lines of the third paragraph of the introduction have been deleted, together with other changes to the text.
We moreover agree with statement from the reviewer that 20th-century philosophy of science was dominated by physicists and devoted to the reconstruction of physics. This is not the intention in the paper: we are a team of authors from different disciplines and we employ recent and contemporary philosophies of science (post-Kuhnian and semantic PS) that have also denounced this "physicalism" in PS and that have proposed frameworks to prevent it.

Deleted text:
There has been sustained criticism to traditional teaching supported by a simplistic and reductionist approach to human knowledge and treating each school discipline separately (Connor et al. 2015).

Modified text:
In primary and secondary schools, the disciplines encompassed in "STEM" —Science, Technology, Engineering and Mathematics— have usually been studied as separate school subjects, with little effort directed towards non-anecdotal integration. "Integrated STEM education" is one of the most recent interdisciplinary proposals and, under its umbrella,

school disciplines are beginning to be integrated in an educationally fruitful way. STEM as a renovated approach is gaining ground nowadays, despite the infancy of its philosophical analysis; explicit epistemological discussion of integrated STEM proposals is either absent or blurred. The overall aim of this paper is therefore to establish an initial framework for philosophical discussion, to help analyse the aims and discourse of integrated STEM education, and consider the implications that adopting any particular epistemological view might have on the aims for general education, and on the construction of science curricula oriented towards citizenship and social justice. We envisage humanist values for integrated STEM education and, after revisiting the currently proposed relationships between the STEM knowledge areas, we adopt a model of a "seamless web" for such relationships that is coherent with those humanist values. A few issues emerging from this model are addressed through the lens of the so-called Family Resemblance Approach, from the field of research on the nature of science, in order to identify some potential central features in a hypothetical "nature of STEM".

Modified text:

The families of disciplines referred to by the acronym STEM —Science, Technology, Engineering and Mathematics— have historically been taught, at the primary and secondary levels, with different levels of emphasis and extension, but always as markedly separate school disciplines. Little effort has been directed towards non-anecdotal, substantive integrations, driven by encompassing educational aims. We could characterize such an approach towards science and technology education using the ideas from Connor and colleagues (2015) of a "simplistic reductionism" in traditional teaching, which would give more relevance to intradisciplinary academic standards than to socially relevant questions and problems.

Disciplinary integration, or interdisciplinarity, has a theoretical background of its own and a fairly broad range of conceptualizations (Chubin *et al.* 1986; Klein 1990; Torres Santomé 1994); although conceptualizing —from a historical point of view— this notion may imply going back in time to philosophers such as Plato. The very concept of *interdiscipline* has mainly been studied during the 20th century, from quite different theoretical perspectives (Frodeman *et al.* 2010). A well-known example would be the ideas of the Austrian philosopher, Karl Raimund Popper (1963), who considered that scientists did not study disciplines but problems, which can in many cases traverse the traditional boundaries of various disciplines. The notion of interdisciplinarity has also been examined in education over the past century. For instance, American pedagogue John Dewey (1929) analyzed educational science as a field integrated by various disciplines, aiming at scientifically studying the different aspects of education, understood as a complex social undertaking in several spheres of action.

Reviewer's comment:

Moving beyond the abstract, we find, low and behold, that the authors are concerned specifically with "school science" as if philosophical analysis of the sciences was done by philosophers of science with reference to how science is taught in school. This is a silly claim. The distinction between school science (what is taught in schools about sciences) and science (what scientists actually do) is certainly an appropriate distinction to make, but the suggestion that there are philosophers of science who study school science, as opposed to science is ridiculous.

Authors' response:
This claim was not in our manuscript; it is probably a matter of poor phrasing, which we have now revised in the whole text. In any case, there have been plenty of philosophers (and historians) of science who have studied school science along with (and not as opposed to) the science of scientists (Patrick Suppes, Joe Sneed, Gaston Bachelard, Thomas Kuhn, Ron Giere, Mario Bunge, Mary Joe Nye, Héctor Palma, Ulises Moulines, etc.).

Significant change:
The philosophical tools that we will apply for our analytic task were of course originally designed to understand scientists' science –and subsidiary, other "disciplined" fields. Accordingly, we will first perform an examination of the STEM disciplines *as they are developed by their professional practitioners*. This philosophical analysis will then be used to extract lessons for the school counterparts of those disciplines, assuming continuities and ruptures between technoscience and "school science".

Reviewer's comment:
It is fair to say that the NGSS standards now place a renewed emphasis on interdisciplinarity, and that that focus has implications for how issues associated with the nature of science should be taught. But that is not the point of departure of this manuscript.

Authors' response:
We have taken into account this valuable suggestion in our new version of the manuscript. In the third paragraph of the introduction we have added information to recognize the NGSS as an inflexion point. We have also made an attempt at incorporating the reviewer's idea in the initial consideration of our manuscript.

Added text:
Along these lines, the so-called Next Generation Science Standards (NGSS) created by the National Research Council in the US undoubtedly constitutes an inflexion point for the renewed educational emphasis on interdisciplinarity.

Reviewer's comment:
Instead the entire essay is based upon an overly simplistic portray of how science is currently taught, which they castigate as coming from a "mono disciplinary" paradigm cf. Connor et al. (2015). At the very least, the authors should provide more insight into how Connor et al. came up with this perspective because, however appropriate it might be for describing the teaching of engineering, it is not an appropriate way to describe how science is taught.

Authors' response:
We have now tried to present this idea (and other ideas and authors) in a less simplified (or simplistic) version. In this regard, we have modified the text of the first two paragraphs of the introduction.
In any case, the reviewer discards the idea on the basis of the education of biologists at the University, where (s)he cites the multiple disciplines learnt –but these come only from the natural sciences and eventually math. The reviewer does not point out explicit teaching of technology or engineering in a grade of Biology.

Modified text:
The families of disciplines referred to by the acronym STEM —Science, Technology, Engineering and Mathematics— have historically been taught, at the primary and secondary levels, with different levels of emphasis and extension, but always as markedly separate school disciplines. Little effort was made towards non-anecdotal, substantive integrations driven by encompassing educational aims. We could characterize such an approach towards science and technology education using the ideas from Connor and colleagues (2015) of a "simplistic reductionism" in traditional teaching, which would give more relevance to intradisciplinary academic standards than to socially relevant questions and problems.
Disciplinary integration, or interdisciplinarity, has a theoretical background of its own and a fairly broad range of conceptualizations (Chubin *et al.* 1986; Klein 1990; Torres Santomé 1994); although conceptualizing —from a historical point of view— this notion may imply going back in time to philosophers such as Plato. The very concept of *interdiscipline* has mainly been studied during the 20th century, from quite different theoretical perspectives (Frodeman *et al.* 2010). A well-known example would be the ideas of the Austrian philosopher, Karl Raimund Popper (1963), who considered that scientists did not study disciplines but problems, which can in many cases traverse the traditional boundaries of various disciplines. The notion of interdisciplinarity has also been examined in education over the past century. For instance, American pedagogue John Dewey (1929) analyzed educational science as a field integrated by various disciplines, aiming at scientifically studying the different aspects of education, understood as a complex social undertaking in several spheres of action.

Response to Reviewer 2

Reviewer's comment:
Your position paper contributes to the problem of how STEM education should be grounded in philosophical / epistemic considerations about science, technology, engineering and mathematics. As far as I understood, your general objective is to contribute to a humanist / full-citizenship approach towards STEM which substantially exceeds the more traditional economy-driven perspective (fostering career choices, science literacy). It can contribute to the body of literature in this field. I read your manuscript with great interest. Most of your ideas are clearly reported and based on a broad variety of academic resources. In this way, your work generally contributes to a more sophisticated understanding of STEM.
Nevertheless, some aspects appeared quite irritating to me and should be considered for revision:
* You raised the idea that a philosophical framework might contribute to a clarification of aims and discourses in STEM (p. 2). I wonder, is this all we need for such a clarification? Next to a philosophical analysis we need a better understanding of the citizen-perspective, the problems citizens are facing and in which ways STEM might support them in doing so. I wonder where are the limitations of your approach? Are there any problems and concerns a philosophical perspective cannot deal with? In which ways and to which extend are perspectives needed beyond a philosophical approach (economic, social, educational, students' perspectives…). In a nutshell, I am asking for a description of the limitations of your approach.

Authors' response:

We totally agree with this comment. Science education for citizenship is of course a complex issue that requires contributions from different social actors and different kinds of knowledge. We have tried, in our revision, to state the scope and limitations of a strictly philosophical analysis.

Added text:

The philosophical tools that we will apply for our analytic task were, of course, originally designed to understand scientists' science –and subsidiary, other "disciplined" fields. Accordingly, we will first perform an examination of the STEM disciplines *as they are developed by their professional practitioners*. This philosophical analysis will then be used to extract lessons for the school counterparts of those disciplines, assuming continuities and ruptures between technoscience and "school science".

Critically analysing integrated STEM and establishing some foundational guidelines, to incorporate it into standard science education, will of course need far more elements than only an examination of its philosophical basis. Other disciplines, such as the history and sociology of science, pedagogy and curriculum theory, school policy and economics, and knowledge from non-disciplinary fields and spheres of human activity —equity, ethics, institutional administration, curriculum co-construction, social justice, cultural diversity, management of controversy, etc.— are essential resources. The limits of our proposal in this article are therefore those imposed by our mainly philosophical approach, which cannot fully deal with the complexities of all the interactions of the actors within science education, for instance in terms of interests, worldviews, power, and legitimation.

In the first place, we will examine the "natures of" the four big disciplinary spaces comprised in STEM, in terms of the kinds of intellectual activities that they involve, and of the types of knowledge produced by such activities. For this examination, we will use different contributions from recent and contemporary philosophy of science and technology, seeking to characterize some core epistemic aspects of S, T, E and M.

We will subsequently move to an epistemological analysis of the possible dialogues between such natures, aiming at constructing a web-like depiction that is as coherent as possible. The aim is the eventual construction –via analogical mechanisms between professional practice and interdisciplinary teaching- of an "integrated nature of integrated STEM". Our inspiration for this, of course, is the field of the nature of science in science education, which mainly draws from considerations coming from the philosophy of science of the second half of the 20th century. Our main source will be Gürol Irzik's and Robert Nola's proposal to use Wittgensteinian family resemblances, in order to argue in favour of the "interconnectedness" of our emerging nature of STEM.

Beyond the scope of this essay, further analyses are due on other significant aspects of the foundations of STEM, using the theoretical contributions from other disciplines and from the knowledge possessed by other groups of stakeholders –teachers, students, families, administrators, decision-makers, evaluators, etc.

Reviewer's comment:

* I liked your discussion of the "seamless web". Nevertheless, this perspective widely ignores that disciplines are strongly separated on an institutional level (The FRA interpretation of Erduran and Dagher might help here): science and engineering are often taught at different universities or universities for applied science. They are usually located at different faculties.

Scientists or engineers are presenting their research on different conferences and journals and they build quite separated scientific communities. As a result, on an institutional level the NOS, NOE, NOT, NOM are far from constructing a seamless web. According to my impression your manuscript is lacking this perspective.

Authors' response:
We also agree with this portrayal of the institutional framing of STEM education. The idea of the "seamless web" transcends this difficulty, since it refers to the coordinated work of the natures of the different disciplines in school science, as we clarified on p. 13-14. On the other hand, the FRA framework is a useful support for our theses, and that is why we have incorporated more details in the fourth paragraph of the conclusions and in many other parts of the text.

Added text:
We would like to note that, as powerful as the "seamless web" perspective may be —both at the analytic and the educational levels— it disregards the fact that professional STEM disciplines are strongly separated at an institutional level. Nevertheless, the idea of a "seamless web", as introduced in the context of this paper, is intended to transcend this difficulty, since it refers to the coordinated work of the natures of the different disciplines *in school science*.

Reviewer's comment:
* I am missing a link in your discussion between the seamless web idea and the goal of full-citizenship. These are both important ideas in your discussion but not yet very well connected. I wonder in which way the seamlessness idea contributes to empowering young people to be better decision-makers in SSI or something alike.

Authors' response:
We have tried to clarify on p. 13 how full citizenship could be better supported by a more coherent (and "web-like") understanding of the nature of S, T, E and M.

Added text:
It is worth stressing that, from the humanistic perspective, we envisage an understanding in integrated STEM education that science, technology, engineering and mathematics are inextricably intertwined and form part of a seamless web of society where politics and economics constitute a central element for preparing young students to engage in responsible action towards a more sustainable and just world. Students will be decision-makers in socio-scientific topics and producers/consumers of new information, knowledge, and technologies. For example, when addressing the problem of the use of plastics, a typical STEM problem, young students may be able to understand the deep connections between chemistry concepts, engineering processes, and technological products as part of the cognitive-epistemic system; such connections are very powerful for producing new knowledge, products, and discourses. But students should also direct their attention towards how STEM disciplines, seen as a social-institutional system, are embedded in a larger socio-economic matrix that may differ at regional and global levels. As a result, students may become able to decide on the actions, for example, with regard to plastics, that should be taken in their contexts. We consider that

all these understandings cannot be achieved, if the “natures of” S, T, E and M are separately addressed at school.

Reviewer's comment:
* On p. 4 the limited impact of STS on education was discussed. I agree with you, but wonder how a similar problem for STEM might be avoided. STEM is a really ambitious educational change which does not fit very well to the expectations and attitudes of more traditional science teachers. In science education, programs and approaches to teaching are changing rapidly, and teachers are often unable to keep up. It often takes decades to implement a curricular innovation in an educational system. Can it not be that the change STEM is causing in secondary science education is faster than the school system can adapt? Almost all authors contributing to the development of STEM are lacking answers to this problem. Maybe you have one?

Authors' response:
We agree with this remark, which we find extremely interesting and important. We do not have a specific solution for such a daunting problem. Although it is not the main focus of the article, in the revised version (p. 4), we expanded the warning about these problems, despite the effort that the STEM movement appears to have to make.

Added text:
These are lessons to be learnt in the current STEM movement (Williams 2011), despite the much greater effort, and the larger amounts of materials and courses, particularly from private and governmental institutions, from which the STEM movement appears to benefit, in comparison with STS proposals.

Reviewer's comment:
Minor remarks:
* p. 2: clarify what you exactly mean when warning that a baby might be thrown out with the bathwater

Authors' response:
We have deleted the expression in its original position in the text. Explanation of the warning contained in it is included in the expanded version.

Modified text:
However, it would be necessary to reflect explicitly upon some *philosophical* issues around the nature of the constituent disciplines and the possibilities for dialogue between them, in order to give substantive meaning to an integrated STEM education. Therefore, the overall aim of this paper is to establish an initial framework *for philosophical discussion*, to help analyse integrated STEM and its aims, discourse and methods, in order to contribute to the task of giving educational rigour and validity to this approach.

Reviewer's comment:
* Next to STS, PUS (public understanding of science) should be considered.

Authors' response:

PUS is indeed an interesting element to incorporate into our arguments. We have included a mention to this approach in our new version (p. 4-5).

Added text:
In this revisited history of STEM, the Public Understanding of Science (PUS) movement should also be mentioned. With aims close to those of STS, PUS emerged as a movement –and subsequently as a field of studies– in the mid-1980s, as a result of the evidence of an extensive "deficit" among the general public in terms of their understanding of scientific knowledge. Initially driven by scientists who adopted this deficit model —it seemed to be enough for scientists to communicate their scientific knowledge, so as to fill the public's "empty vessels" (Seakins and Hobson 2017, p. 443)— PUS evolved, over the following ten years, into the notion of "public engagement with science", implying a democratization of science, in which research and technologies should be steered with reference to public values (Short 2013).

Added text:
Seakins, A., & Hobson, M. (2017). Public understanding of science. InK. S. Taber& B. Akpan (Eds.),*Science education. New directions in mathematics and science education* (pp. 443-452). Rotterdam, Netherlands: Sense.

Short, D. B. (2013). The public understanding of science: 30 years of the Bodmer report. *School Science Review, 95*(350), 39-44.

Reviewer's comment:
- The notion of fully engaged citizenship should be briefly elaborated.

Authors' response:
Done. We have briefly expanded on this notion (p. 6).

Modified text:
One big lesson that we learned from the so-called "new philosophy of science" of the 1960s to 1980s is that the heavily scientistic view that dominated meta-scientific reflection in the 19th and the 20th century –and which now seems to be implicit in many STEM proposals- can scarcely capture the complexities of the relationships between science, society, culture, and values. Our proposal is to detach integrated STEM education from its original ideological matrix, which does not contemplate such lessons. This task is possible in the case of many powerful educational ideas; it has already been done with inquiry-based science education and with competencies as innovative curriculum elements, among other topics. The ideological origins of the concept of STEM, in our opinion, would not matter in our educational context; what is essential is that the resulting, re-contextualized, approach is pedagogically powerful and compatible with the current socially proclaimed aims for education. The "philosophies of disciplines" that we want to select for STEM should be directed towards infusing a humanist stance and worldview into science curricula that is compatible with fully engaged citizenship; thus, the epistemological frameworks that we choose should support a science education that prepares students to engage in responsible action towards a more sustainable and just world (Hodson 2006).

Reviewer's comment:

*p.5: Elaborate on the way how post-Kuhnian views and semantic view on theories might contribute to a foundation of STEM

Authors' response:
Done. We have elaborated on this issue (especially on p. 6).

Modified/added text:
Following this line of using educational criteria to select philosophical foundations, two recent schools of the philosophy of science, namely post-Kuhnian philosophy of science and the so-called "semantic view of scientific theories", appear very promising when constructing a "temperate" or "moderate" image of science —and perhaps of its relations with technology and mathematics. Such an image –a "third way" between positivism and relativism- recognizes the extremely relevant achievements of technoscience, without hiding its problems and shortcomings. Post-Kuhnianism and the semantic view could also provide a few elements to help in the conceptualisation of pure and applied mathematics, computation, informatics, engineering, design and technological innovation.

Added text:
Post-Kuhnian philosophy of science, with its overtly naturalized (i.e., non-normative) approach to the study of the nature of science, provides very robust insights, since it examines "science-in-the-making", especially focusing on epistemological topics such as practices, agents, aims, values, languages, and communities. The semantic view of science, strongly influenced by the linguistic and pragmatic shift in philosophy after World War 2, provides a very detailed and founded characterization of models and modelling that relates to key epistemological issues, such as reasoning, inquiry, argumentation, judgment, and context. We find all these topics necessary for a construction of a prospective "nature of STEM" for science education, promoting the "styles" of thinking and practice in the different groups participating in the production of science *as a human enterprise* (scientists, technologists, entrepreneurs and inventors, policy-makers, financial supporters, evaluators, users, general public...).

Reviewer's comment:
* p. 5: you are briefly discussing the role of arts in a STEAM framework, but I still wonder if and to which extend arts might play a substantial role in your discussion.

Authors' response:
Arts do not play a substantial role in our main argument. We have only contended that some of the STEAM proposals seem more committed to the ideas of solving socially relevant problems than the "hard core" of STEM proposals. We have tried and clarified this.

Modified/added text:
Finally, and along this same line of providing sound foundations for a more humanist perspective for integrated science education, we believe, as previously indicated, that STEAM education appears to be a more balanced option. In particular, the inclusion of arts appears to offer a natural and broader platform for transdisciplinary inquiry and opens the door for sociocultural integration (Zeidler, 2016). It is our contention that any STEM proposal that does not include the contribution of the arts, the transversal focus of design, the

drive for authentic disciplinary integration, and a discussion of values "necessarily excludes important areas that inform and contextualize science by grounding them in sociocultural contexts" (Zeidler 2016, p. 17). Nevertheless, in this paper, it is not our intention to present an explication discussion of the epistemology of arts.

Reviewer's comment:
* p. 8: Please, elaborate your ideas on simulations a bit further

Authors' response:
Done. We have added a fragment of text to this effect (p. 10).

Added text:
All these features can for example be seen in scientific simulations. When transforming mathematical models into discrete algorithms that imitate the behaviour of systems, scientists should take into account the computational cost of the resulting algorithm, as well as the possibility of that algorithm being unstable, and thus producing unreliable results. In those situations, they need to simplify the model by ignoring or discarding some factors, by reducing the model's degrees of freedom, by adopting what are known to be rather unrealistic assumptions of symmetry, by including mathematically simple relations with no direct connection to the original differential equations, or by substituting the real physics of a process, which might be overly complex, with phenomenological relations. In short, the "parametric" relations that appear in a simulation often have no direct counterpart —in a strictly realistic sense, from a naïve realist point of view— in a real system (Authors). However, these procedures have for a long time been attributed to technology rather than to science, in the view of several scholars such as Bunge.

Response to Reviewer 3

Reviewer's comment:
The goal of this position paper is to propose an epistemological framework to support discussions of contemporary STEM education efforts. The authors provide a brief overview of other efforts in interdisciplinary education (STS, STSE, SSI, e.g.). It is interesting to me that the authors chose to focus on STEM, which in its acronym, includes no reference to society or to the humanistic goals of STS and SSI - although they are making an effort to show that STEM itself can aim for societal good and humanistic purposes.

Authors' response:
One of our theses is precisely this one commented by the reviewer. "Standard" or "orthodox" STEM has no "S" for society and no substantive connection to the social and human implications of science and technology, beyond some superficial considerations on "impact". Our proposal is to see STE(A)M through the lens of SSI or other proposal with clear humanistic orientation. This can be better seen in the modified and expanded version of our manuscript.

Reviewer's comment:
In particular, I was hoping that they would attend to the increasing diversity of our society under the still dominant White Western scientific paradigm(s) and restart/continue the

"radical shift from the status quo" (p. 3) begun by Aikenhead and his peers. Is this shift necessary for making the work socially relevant and humanistic? While this question was brought up in my mind, I did not see a response to it in the paper.

Authors' response:
Contributions from critical pedagogy and critical curriculum theory are important for our ideas and underdeveloped in our original manuscript. We have tried and incorporated more remarks along this line, on p. 5-6.

Modified/added text:
The axiology underlying "orthodox" STEM needs a traditional, *scientistic* epistemology, which deposits faith in the scientific method as a more or less infallible way of producing justified knowledge that can be later applied to an extensive, "aseptic" transformation of the world that, through a linear path, would bring economic development.
Nevertheless, we believe that another theoretical approach to integrated STEM education is possible, based on a more "contextualist" view of the nature of technoscience and laden with more humanist values. Such an approach should include a substantive connection to the social and human implications of science and technology, beyond some superficial considerations on "impact". It should be aimed at student engagement in more active and participatory community-grounded science, including calls for equity, social justice, and full citizenship (Calabrese Barton 2012). So, we envisage an integrated STEM education within a "humanistic" perspective (Aikenhead 2015) that would have the aim of equipping citizens with the tools they need to live in society and to contribute to it, based on the "pillars" of citizen education: disciplinary knowledge, know-how, substantive comprehension, meta-knowledge, competencies for life and coexistence, competencies for responsible action (Delors 1996). As we said, it is clear to us that only some epistemologies fit with the humanist values that we envisage: we need to retrieve conceptions of science, maths, engineering, computer and information science, and technologies that move away from technocracy and conceptualize disciplines as social organisations, knowledge communities, and cultural legacy.

Added text:
Calabrese Barton, A. M. (2012). Citizen(s') science. A response to "The future of citizen science". *Democracy&Education*, 20(2), 1-4.
Delors, J. (1996). *Learning: the treasure within. Report to UNESCO of the international commission on education for the twenty-first century*. Paris, France: UNESCO.

Reviewer's comment:
I was also intrigued by the authors putting forth a holistic, thoroughly interdependent (among the four disciplines) vision of STEM. I appreciate this effort; a fully integrated STEM approach would be more useful than one that claims to include all disciplines but in actuality focuses on one and brings in others peripherally or artificially. The proposed framework might provide a way to judge integration among the four fields and help use to see when curriculum and instruction (and, to be really powerful, standards) are thoroughly and authentically integrated, or superficial, or unbalanced toward one discipline.

Authors' response:

We have found this remark extremely useful. In the conclusions, we have incorporated the idea of using our framework as an evaluation tool for the degrees of epistemological integration in STEM proposals.

Added text:
We have presented here our –still very tentative– framework as a way to conceptualize a STEM education of highly formative value and as a basis to construct integrated proposals aiming at ambitious educational objectives. However, such a framework might also prove to be a way to *assess* the quality and extent of integration among the four STEM academic fields in STEM education proposals[2]: it might help us recognize when curriculum, instruction and evaluation show authentic *theoretical*, *methodological* and *axiological* integration in a thoroughly transversal manner that co-ordinately directs S, T, E and M towards the "bigger" purpose of cognitively and socially relevant problem-solving.

Added text:
[2]Our thanks to an anonymous reviewer of our manuscript for pointing out this very suggestive idea.

Reviewer's comment:
In terms of the structure of the paper: Because you are aiming for a "seamless web" framework, and you say that Haraway, Latour (and I hope others that you have knowledge of) have developed philosophies and cultural perspectives that support this model, I would spend more time on this school of thought and less on others - you could summarize the "monodisciplinary" "nature of" philosophies in a paragraph or two, and then delve into the seamless web group more extensively. I think that this would be interesting, up-to-date, and more supportive of your framework.

Authors' response:
We have enlarged the description of the seamless web approach (p. 9). Nevertheless, we maintained the section that addresses the monodisciplinary "natures of", since it summarises relevant epistemological issues for the construction of a nature of STEM that have not been put together anywhere else, as far as we know.

Modified/added text:
These latter models consider that science, technology and engineering form part of a seamless web of society, politics and economics. As stated by Hughes (1986, p. 282): "Heterogeneous professionals -such as engineers, scientists, and managers- and heterogeneous organizations -such as manufacturing firms, utilities, and banks- become interacting entities in systems, or networks". Hughes proposed several examples of webs, both at the individual and at the social level. For example, the seamless web of thoughts of Thomas Edison as expressed in his notebooks, where mixed topics commonly labelled "economic", "technical" and "scientific" appear. Another example is the improvement of the public health system in late 19^{th}-century Germany where no clear distinctions may be established between the goals and means of scientists, academics, engineers, educational and state ministers, and their organisations. This case shows scientific knowledge integrating a seamless web that joins social, political, ideological, and design dimensions along with the conceptual content of science (Hughes 1986, p. 289).

Because of the claimed seamlessness between the interacting elements, proponents of such models often use the post-Kuhnian notion of technoscience in all its theoretical meaning, and so, sociological, technoscientific, and economic analyses are permanently interwoven into a highly coherent web. These models capture most modern technological and scientific practices more accurately, especially in the era of big science —see, among many others, the analyses by Haraway (1997) or Latour (1987).

Added text:

Hughes, T. P. (1986). The seamless web: technology, science, etcetera, etcetera. *Social Studies of Science*, *16*(2), 281-292. https://doi.org/10.1177/030631278601600200 4

Reviewer's comment:

Also, the paper might be more intriguing to science researchers and educators if you presented the framework earlier, and then explained it. We do not need to see all of the thinking leading up to it - although of course we need to see the thinking that supports it, how it can be useful in designing curriculum and/or instruction, and what the potential gaps or weaknesses of the proposed framework could be. This could also help to address the choppiness of the paper; it feels as though theorists and philosophers drop in and then disappear. Use only those who are really important (if they do not directly support your framework) and show the connections among those who do support your framework. Along these lines, I would also bring in the FRA model and your reasons for relying on it earlier in the paper.

Authors' response:

We have made some changes in line with your suggestions (for example, adding references to the seamless web approach and to the FRA model earlier and deleting some paragraphs). Nevertheless, as indicated in the previous comment, we maintained the overall structure of the paper, since we consider that sections 4 and 5 summarize relevant epistemological issues for the construction of a nature of STEM.

Deleted text:

But engineering practice, design and management, although involving knowledge and enabling the acquisition of knowledge, “are not primarily knowledge-producing activities” while “engineering science is” (Houkes 2009, p. 313). So, the precedent statement can be reframed as follows. In the case of science, knowledge about natural phenomena is an end in itself, while engineering science generates models of phenomena that produce useful results —in the form of some kind of product—, even if they offer little explanatory power.

Deleted text:

In addition, a review about the several ways in which authors have tried to establish an “epistemic emancipation” of technological knowledge from its scientific counterpart shows that most of the available studies have not produced refined discussions about this issue and have accordingly failed so far to establish strong arguments for the complete autonomy of technology (Houkes 2009, p. 342).

Added text:

Our idea that it is possible to construct an “integrated nature” for integrated STEM education implies resorting to a higher-level conceptualization that goes beyond the sum of the “natures” of the four distinct components in STEM. Thus, we will present in this article an attempt at partially connecting the epistemologies of the STEM constituents into what we will call a “seamless web”. Nevertheless, in order to characterize such a web, it is necessary for us to depart from the separate natures of science, technology, engineering, and mathematics. In those natures, we will identify and analyse different epistemological views that, eventually combined through family resemblances between them, will be transferred to the STEM approach as a whole.

Reviewer's comment:
To summarize, the authors "consider that the adoption of certain epistemological views inevitably influences the type of values proposed for integrated stem education and vice versa" (152-154). This perspective was not fully developed. What values do the authors hold? How would developing powerful STEM framework serve the needs of a democratic and increasingly diverse society? Responding to this question would be very intriguing and possibly bring back some needed radicalism to current science education discourses, while overlapping with movements for culturally responsive-sustaining pedagogies.

Authors' response:
Our original manuscript is only a first, draft-like attempt at answering these questions. Its seminal character and the space limitations conspire against fully addressing all these complex issues, but we have tried and incorporated these questions and some hints on possible answers.

Reviewer's comment:
I am interested in the possibility of a framework that could help guide our efforts to create science education that is socially aware, and welcoming and supportive of our diverse democracy (if we can keep it). I think that the paper needs focus, streamlining, and a good edit. I hope that you continue with this work so that those of us who care about education that supports work for a better society can benefit from your thinking.

Authors' response:
We hope the new version is clearer, more focused and less choppy. We have modified 30% of the original text in pursue of this aim.
Thank you for your favourable comments and valuable suggestions!