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STEAM for all: a vision for STEM and arts integration

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STEAM for All
A Vision for STEM and Arts Integration.

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Abstract
The arts are a crucial component of human culture, in which we spend large amounts of time and resources as creators, curators, or consumers. As such, they have been historically tightly integrated with the STEM fields. Recently, there has been a push from governments and academic communities to return this integration to the educational arena under the concept of STEAM (STEM+Arts). Here, we give an overview of STEAM's history and purpose and discuss how what has been defined as *Thickly Authentic* STEAM practices can be instrumental for harmonizing the education system's expectations for nurturing children and developing the workforce.

Keywords
Arts Data Diversity Edtech Engineering Equity Inclusion Integration Math Music Science STEAM STEM Technology

STEM and arts.

An ancient account relates the story that Pythagoras, the mythical forefather of Greek mathematics, was preoccupied with finding a way to quantify the perception of sound, in a similar way that a scale can quantify weight, when he walked past a blacksmith's shop and heard consonant sounds (octaves, fifths, and fourth musical intervals). Excitedly, he ran into the shop and started experimenting with the sounds the blacksmiths were making, striking metal rods with varied forces, striking on different types of metal rods, and with hammers of various weights. This experience led him to carry out a series of experiments making sounds with pipes of different lengths, cups filled with different amounts of water, and strings with different lengths and tensions, thus relating the size of the vibrating objects with their frequency, and establishing the mathematical and physical underpinnings of harmonic chords and musical scales (Figure 1).

Although not historically accurate, this tale highlights the role of science and math in understanding human sensory perception in relation to music, and the role of music in inspiring and providing a language for physics and mathematics. Throughout history, music remained an object and an inspiration for scientific research, a link that was expressed in classic education in the quadrivium, the basis of philosophical education, put forth by Plato and used through the middle ages, comprised of Arithmetic, Geometry, Music, and Astronomy (Pesic, 2014).

Figure 1. Pythagoras researching the physical and mathematical underpinnings of musical harmony. From Francinus Gaffurius' *Theoria Musicae* (1492).

Perhaps the best-known personality at the intersection of art and STEM is Leonardo da Vinci. Even though he is often conceived as a polymath with diverging interests, for da Vinci art and STEM were not independent endeavors, as one of the main goals of renaissance art was creating an illusion of reality (Isaacson, 2017). This involved, for example, the use of math to create the illusion of depth through perspective drawing, understanding how objects can be modeled in three dimensions by decomposing them into simple geometrical forms, understanding how light and color are reflected on those forms and filtered through the atmosphere, understanding anatomy, and experimenting with new materials such as pigments and oils to create vivid colors.

These examples highlight that for the renaissance STEAM professionals, creating the illusion of nature involved a deep understanding of nature. And similarly, representing nature is a prerequisite for understanding it, as is also shown in da Vinci's anatomical drawings, Bouguereau's studies of clouds, and countless other illustrators whose work was fundamental for the development of the biological sciences (See relevant websites, The Art of Innovation, BBC).

It is helpful to understand the historical connections between the arts and STEM in order to see the contemporary connections and appreciate the technological aspects of art products of the past and the artistic aspects of technological products of the present. As technology evolves, what we consider "technological" changes over time. If, as computer-pioneer Alan Kay said, "technology is anything invented after you were born," it is easy for contemporary culture to overlook the technological value in the works of da Vinci and others and in the techniques described above. As a counterpart, it is sometimes easy to overlook the artistic value of technological consumer products that are integral to our culture, relegating the idea of *Art* to traditional forms found in museums, concert halls, and academic activities. The development of video games, for example, continues the renaissance's obsession with recreating reality, incorporating its technological advances, and adding newer technologies such as artificial intelligence, physics engines, and haptic interfaces to create a more immersive and flexible environment. Similarly, the Pythagorean inquiry on the nature of sound and music is extended to include the development of electronic techniques for creating music, such as the modular synthesizer (if the reader is old enough to call it technology), the development of software for sound production and editing, and the use of artificial intelligence and signal processing for autotuning the human voice (A History of Electronic Music, see relevant websites). These examples indicate that by taking a perspective that goes beyond the narrow conceptions of Art and Science typically taught in schools, the connections between STEM and the arts are easier to find than to miss.

History and meaning of STEAM education.

The acronym SMET, standing for Science, Mathematics, Engineering, and Technology, was first used by the United States' National Science Foundation in the nineties and was soon scrambled into STEM to avoid vulgar connotations (Breiner et al., 2012). STEM originally designated the four field areas, without an associated educational philosophy, but with an emphasis on training and recruiting a workforce to compete in the international arena. This conception of STEM as a grouping of fields is still used frequently, particularly in policy discussions. Over time, many in the education community came to associate it with integrative project-based and inquiry learning, as is typically experienced by STEM professionals (Breiner et al., 2012), who need to bridge disciplines to solve problems. The term gained popularity in the 2000s and led to the opening of STEM schools, the designation of specialized district administrators, and professional development programs.

The first written reference to STEAM was putatively (Mejias et al., 2021) by Yakman (Yakman, 2008) as an idea for greater integration of STEM and the arts, although the idea of integrating arts and STEM fields was not new (see for example (Robinson, 2013)). As the recognition of the need for integration and the acronym gained popularity, many of the STEM programs added the connections to the arts and became STEAM.

The US government has promoted STEAM education through funding and conferences (Harrell & Harrell, 2010), and the US' House of Representatives released a resolution for "adding art and design to federal programs that target [STEM]" with the goal of encouraging innovation and economic growth. (Langevin, 2015)

Goals of STEAM

Enough of the STEM and STEAM literature is devoted to defining, redefining, criticizing, and disentangling the meaning of the term (Breiner et al., 2012; Colucci-Gray et al., 2019; Mejias et al., 2021). We do not intend to add to that discussion but to state that the definition of STEAM varies with the stakeholder, with a general conception of project-based learning integrating the STEM fields and the arts. It should be noted that, in practice, the arts are frequently not included, for example, many self-proclaimed STEAM programs are robotic challenges (Colucci-Gray et al., 2017). The fact that experiences as such are categorized as STEAM perhaps reflects the fact that STEAM programs inherit STEM values, and that many can see the aesthetic and artistic value in the engineering processes (Harrell & Harrell, 2010). Since a large part of society's interest in STEAM is its relationship to the arts, and since this is a chapter about STEAM in a volume about STEM, here we emphasize the importance of the arts.

Just as STEAM means something different for different people, the goals for adopting STEAM education are varied, with the common assumption that children find the art-making process engaging and personally relevant. Of particular importance for their role in establishing educational policy is the view of policymakers, represented among others by the US house of representatives, whose resolution referenced above stated that:

1) Innovative practices of art and design play an essential role in improving Science, Technology, Engineering, and Mathematics (STEM) education and advancing STEM research.
2) Art and design provide real solutions for our everyday lives, distinguish United States' products in a global marketplace, and create opportunity for economic growth.
3) Artists and designers can effectively communicate complex data and scientific information to multiple stakeholders and broad audiences.
4) The tools and methods of design offer new models for creative problem solving and interdisciplinary partnerships in a changing world.
5) Artists and designers are playing an integral role in the development of modern technology and manufacturing.
6) Adding art and design to Federal STEM programs has the potential for recruiting into STEM fields children from underrepresented ethnic and economic backgrounds.

Some of these US House's statements parallel scholars' assertions that the inclusion of the arts helps develop "creativity, problem-solving skills, exploration of uncertainty, ambiguity, and fuzziness" (Colucci-Gray et al., 2017). The idea that inclusion of the arts can *infuse* STEM practice with those values will be surprising for STEM professionals, who know the importance of creativity in STEM practice, and perhaps reflects the general conception of STEM as uncreative, developed over years of engaging with science through uncreative schooling practices. Furthermore, there is no clear evidence that the creativity exercised through art practices transfers into STEM practices (Perignat & Katz-Buonincontro, 2019). It is important to note, however, that participating in a STEAM activity gives children the opportunity to *exercise* their creativity through the creation of art artifacts, with which they are often very engaged. An opportunity that they would not have otherwise.

The US House's resolution, as well as some scholarly work, indicates that STEAM is a way to engage underrepresented students in STEM fields, although the mechanism is not usually articulated. Because of the cultural relevance of the arts, and the personal relevance in terms of student interest, arts integration can achieve several dimensions that are useful in promoting equity and diversity in STEM education: They approach learning as a cultural accomplishment, allowing for science understanding to grow out of the students' lived experiences. They relate youth discourses to scientific discourses, allowing children to express their understanding in their own language. They build on prior interest and identity, as they relate to the artistic practices, tastes, and identities that the children bring. They leverage the students' cultural funds of knowledge, as they relate to the art-making practices of their communities. They make the diversity visible, highlighting the artistic (and technological) accomplishments of creators from diverse cultures and backgrounds. And they value multiple forms of expression, allowing the children's knowledge to be assessed not by standardized exams but by the creative process and the artistic artifacts that the children produce (National Research Council, 2012).

Although scholarly work generally does not report on the effectiveness of art integration programs to engage underrepresented children in STEM (Colucci-Gray et al., 2017; Mejias et al., 2021; Perignat & Katz-Buonincontro, 2019), some evidence supports this claim. An example is these authors' educational program connecting music with the physics of sound and waves (Minces et al., 2021), applied with low-income and underrepresented (Latinx) eighth-grade children in a US school near the Mexican border. In this experience, children used computers to visualize and edit sound, carried out physical hands-on explorations of vibrating objects, and used their knowledge to create musical instruments. Participating in the program significantly increased the children's perception of themselves as scientists and their intention to pursue science careers, and it greatly increased their engagement with their science class.

Because the arts are manifested as projects or artistic investigations, they are naturally fit for STEM education's project-based ethos. In the example above, when children use a sound editor to create a sound composition they are making an art piece. In the process, they are visualizing the sound's waveform, which is the physical representation of sound, they are applying signal processing transformations to that waveform (for example changing the sound's speed), they are connecting those transformations to human perception (for example noticing that waveforms that evolve faster are perceived as having a higher pitch), and they are observing that superimposing sounds is equivalent to superimposing waveforms. Furthermore, children are beginning to acquire skills that are immediately useful outside of school, and that are connected to the world of work, including sound engineering but also any field that requires recording and manipulating signals. In our program, these connections are highlighted by a series of mini-documentaries profiling young underrepresented people in fields related to sound and waves. Another notable example of the power of music integration for engaging underrepresented students in STEM fields is the popular Earsketch programming platform, in which children use computing to create electronic music (Freeman et al., 2014). In both these types of experiences, the arts and STEM are intertwined, as the art form is inherently technological, and participating gives children agency not only as artists but as STEM creators. These types of experiences can be qualified as *Thickly Authentic STEAM* experiences, defined as having a) personally meaningful learning experiences; b) learning that relates to the world outside of the learning context; c) learning that encourages thinking within a particular discipline (for example sound production); and d) allowing for assessment that reflects the learning process (Freeman et al., 2014; Lee & Butler, 2003; Shaffer & Resnick, 1999).

In contrast with artistic STEM projects, some experiences reported as STEAM involve art projects about STEM fields (Mejias et al., 2021), an example being interpretative dancing about planetary motion (Glinkowski & Bamford, 2009). The latter kind of experiences put arts as subservient to STEM (Robinson, 2013), and position children uniquely as artists and not as STEM practitioners. It is reported that the vast majority of arts integration reports follow this subservient model (Bamford, 2006; Robinson, 2013). A problem with these subservient experiences is that they do not position the children as curious and creative participants in STEM/STEAM practices, reinforcing the popular idea that science is an established body of knowledge guarded by “others”, and children’s creative practices associated with science can only be making art about it. The subservient model, however, is not without advantages. It is possible that the subservient model might serve the STEAM goal of effectively communicating scientific data, although there is no guarantee that children have a deep understanding of what they are doing art about (Colucci-Gray et al., 2017), and there is no evidence that these types of experiences actually improve science communication. Another advantage is that participating in a subservient art experience might be better than the alternative, for example, dancing the planetary motion might be better than learning about it by sitting down and staring at a whiteboard. Subservient art might also offer mnemonic advantages and bring art and movement to a school day that lacks them otherwise, particularly in low-income schools (Bequette & Bequette, 2012).

The US House resolution recognizes a goal in STEAM education that is generally overlooked in scholarly articles, which is adding the value of art and design in the development of consumer products. This is better exemplified by the carefully designed consumer products of Apple –see Steve Jobs’s Stanford commencement speech for an account of the influence of art in the development of Apple products (Jobs, 2005)– which is currently the most valued company in the world, and it can be argued that Facebook and Microsoft, two of the other technology giants, owe their success not to cutting edge technologies but to their innovations in design (Petzold). The goal of adding value is notable in that it sees STEAM not merely as a conduit to better or more STEM, but as valuable in itself and integral to the economy.

Given the goals typically assigned to STEAM education, it is surprising that evaluations of STEAM programs generally focus on the children's acquisition of domain knowledge (and without control groups that would allow an understanding of STEAM's differential contribution). The focus on domain knowledge treats STEAM as a pedagogy, in the sense of "a method for teaching something". The goals above, however, reveal it not so much as a pedagogy, but as a policy regarding what should be taught, why, and for whom, a reflection on what education is for.

STEAM's reach and barriers

Published reports of STEAM experiences have a large bias towards elementary school or after-school programs (Colucci-Gray et al., 2017). Published reports, however, are created within the scholar community, and are not representative of more popular STEAM practices on the ground. To understand its real reach, we carried out informal interviews with leaders in our local, and very active (Wired Magazine, 2019), STEAM ecosystem (see acknowledgments), an approach similar to Colucci et. al. (year). These leaders have created curricula, fairs, and professional development opportunities reaching more than a million students. Although there are no precise statistics, they agree that STEM and STEAM experiences decline in middle school and high school, and are more prevalent in out-of-school environments. Through our interviews and personal experience developing a popular music integration program, we have identified several barriers to implementation, which become more prominent in higher grade in-school contexts. Some of these barriers coincide with the findings of a working group of policy experts led by the *Education Commission of the States* and the *Arts Education Partnership of the US* (Dell'Erba, 2019).

1) Siloing: Early grades are guided by one non-specialized teacher, which makes it easier for them to apply integrative subjects. As grades increase, so does teacher specialization and subject matter siloing. In such a context, teachers need to collaborate if they are to apply integrative experiences while fulfilling the standards. This approach is taken in the well-known High Tech High School System (Wagner & Dintersmith, 2015), but teacher collaboration is much harder to implement in public schools with large class sizes and overburdened teachers. The lack of siloing also explains why STEAM is more frequently applied in out-of-school programs in which instruction does not need to be specialized. 2) Curricular pressure: Teachers are often pressed to teach a rigid curriculum or a set of standards that might not be possible to align with STEAM experiences (Dell'Erba, 2019). Whereas this is true for all grades, it is particularly influential in higher grades, where curricular topics become more microscopic and abstract. For example, it is straightforward to create an engaging STEAM activity around the first grade US standard *connecting sound and vibrations*, because the standard reflects a phenomenon that children encounter regularly, for example when they stand next to a bass speaker or drum, and because it can be directly

linked with the creation of musical instruments. In contrast, we have not been able to create a personally meaningful activity linked to the middle school standard addressing *wavelength*, because wavelengths cannot be felt, are hard to visualize, and are not relatable to the children's everyday experiences. 3) Teacher preparation: an important barrier across grades is teacher preparation (Dell'Erba, 2019). This does not only involve teaching teachers how to implement specific STEAM experiences, but also requires changing rigid teaching practices that are over-reliant on memorization and testing as a way to measure the children's performance. 4) Teacher time commitments: teachers are often overburdened, serving several classes with more than 30 students. The time commitment and the stress of classroom management leave them little time and energy for preparation, collaboration, and carrying out the type of personalized work that supervising STEAM student creations might require (Dell'Erba, 2019). 5) Research focus: because published reports of STEAM experiences are created within the scholar community, they typically involve the participation of highly trained professionals and subject domain experts, and often involve small groups of highly motivated students participating in out-of-school programs. This is problematic because the resources thus created are hard to extrapolate to less motivated students, less well-prepared facilitators, and harder curricular constraints.

STEAM is an attempt to bring to the classroom an integration of meaningful personal interests, project-based learning, performance evaluations, communication, and collaboration. These values run counter to the structure of the educational system, which is siloed, individualistic, test-oriented, understaffed, and focused on subject domain standards that children might not find a personal connection with. In this context, two strategic questions arise: 1) How can the scholar community improve the children's educational experience given the current systemic constraints?; and 2) What radical transformations should the scholar community envision and advocate to implement in the next round of systemic reform? The next two sections explore these questions.

Using STEAM to improve educational experiences within the systemic constraints

Without denying the value of out-of-school programs, focusing on school settings has the potential to engage institutional structures serving many more children, including those that do not already have a science identity that led them to join an out-of-school program and are therefore poised to benefit the most. The educational program being developed by these authors has been growing within, and in partnership with, actors in the formal school system, and the resources thus created are widely used in the US and are starting to be used globally (Nagarajan et al., 2020). Here, we draw on our experience growing the program (Minces, 2021) and our conversations with the STEAM leaders to address the implementation barriers.

A key factor for growing the program is the alignment with the curricular standards, which addresses the issue of curricular pressure mentioned in the previous section. Schools and teachers are oftentimes eager to implement resources that they perceive will engage their students, and will need a minimal measure of standards alignment to be able to do so. Therefore, the standard alignment can sometimes be rather loose, partial, or include STEAM experiences in combination with less meaningful materials. For example, our curricular resources integrate music when addressing the relationship between frequency and pitch, but are much drier when addressing the concept of *wavelength*.

Even allowing for loose alignments, some standards are so far removed from the children's everyday experiences that it cannot be expected that they will be addressed through an Authentically Thick STEAM project. In that case, a subservient art experience always offers the possibility of children making an art presentation about the standard, which might be better than the alternative.

With regard to teacher implementation, it is important that the resources help alleviate, rather than increase, the teachers' burdens. STEAM is a great opportunity to engage teachers, since they can also participate in the joy of the art-making process, which likely increases the likelihood that they will participate in teacher training. Resources should be extremely easy to start implementing, in what Resnic calls low floor (Resnick & Robinson, 2017), and allow for deeper engagement (high ceiling). A low floor includes activities requiring minimal or easily available material resources. For example, using web applications can be much more accessible than using downloadable software, which can be difficult to install on the schools' computers or on the students' devices. A low floor also means designing tools that are easy to use and that are engaging from the first moment. Involving teachers in the design process can be very helpful for fulfilling those goals (Minces, 2021). Another factor facilitating the implementation of STEAM experiences is to provide rubrics that allow teachers to guide the art-making process and evaluate the children's work with less reliance on testing, and with less time spent analyzing each artifact (for example, grading the children's compositions). Easing the implementation of a program will not only facilitate the work in the classroom but will also streamline the teachers' professional development. Regarding research, achieving broader implementation requires a shift towards policy-based research (List, 2022), that is, research that from the outset takes into consideration the possibility of scaling up the results.

A STEAM-inspired vision for education

The section above describes strategies for improving the children's educational experience within the limits of the educational system. This section discusses how STEAM can inform future rounds of systemic reform, which requires a reflection on what education is for (Biesta, 2015). The educational system does not have a clear overarching goal. Rather, it has adopted the goals of different stakeholders, which in turn might be different and contradictory (Labaree, 2012). The state might be interested in forming citizens with coherent national values and in developing the workforce to serve the economic and strategic needs of the country. Parents might value the educational system for providing a place for childcare and improving their children’s economic outlook. Teachers might care about leading a classroom where students are intellectually engaged while complying with the school authorities by implementing the new set of standards and preparing children for the test. The goals for principals might be to manage the children’s behavior and improve the schools’ statistics by increasing the number of students pursuing higher education. Children have no choice but to participate in the system and, young children in particular, might not be so concerned about the future. They might be very interested in socializing, in not being bored, and in learning something, although not necessarily what they are expected to learn. An additional stakeholder, different from the child, is the adult that the child will be, which emerges slowly as the child approaches high school graduation and faces the need to sustain herself or himself. A goal for that adult is to have an occupation that provides life quality, which could involve economic well-being, intellectual fulfillment, or a sense of purpose. Successful reform must acknowledge and harmonize all these goals that at times appear to be in tension, in particular the state’s goal for developing a specific type of workforce versus the children's personal interests. Our goal as researchers is to emphasize the interest of the children to help create a more joyful learning environment, without disregarding the interests of other stakeholders.

The policymakers’ and society’s interests are expressed in the curriculum and activities carried out in schools. In the United States and England, which have influenced educational systems and science education throughout the world, curricular subjects have been a matter of fiery debates and widespread reforms (Atkin & black, 2007; DeBoer, 2014). Three main conceptual currents have informed those reforms, with elements of them alternating and taking prevalence over time. One current, dominating in the late 19 century, and referred to here as experiential, emphasized science practices and direct observation of everyday and natural phenomena. Another current, prevalent in the first half of the twentieth century in association with the progressive movement, and briefly reemerging in the sixties, emphasized the curricular subjects’ value to society, value to the students, and technological applications in nascent industries. The present moment inherits the values of the education reform born during the cold war’s fight for technological supremacy in the fifties, sometimes referred to as the Sputnik era of reform, and that regained strength in the eighties in the context of international industrial competition. The latter current reflected the value that society assigned to cutting edge scientific knowledge, and was shaped by the advice of prominent scientists, who advocated for including curricular subjects associated with the latest advances in their fields and the corresponding higher education courses, in what Atkin and Black (2007) call “scientists’ science”. The latter era also saw a great increase in the value that society assigned to higher education (Baker, 2014), and in the number of people pursuing higher education, with the consequent need to sort what children could attend what institutions (Sandel, 2020). This confluence of factors produced a science and math curriculum that focuses on preparing children for pursuing careers in STEM through higher education paths, and sorting the children that can go through the hoops that such preparation requires. This ethos is captured in the popular model of STEM workforce development as a pipeline (Cannady et al., 2014; Metcalf, 2010), in which children enter at one end and emerge on the other as adult STEM professionals, with the problem that some children, those that cannot go through the hoops, drip off the pipeline, which is therefore referred to as being leaky. We note that the pipeline model is partially different in some countries in which an early tracking system sorts children putting them on a path to higher education or to technical careers through vocational schools. Such a system, which could be modeled as a bifurcating pipeline, has the advantage of producing a large pool of necessary mid-skilled labor and offering young people a safe path to economic security (Newman & Winston, 2016), but it has the disadvantage of sorting children early in life, making it difficult for someone to change and cross trajectories, perpetuating social differences, and creating resentment.

Given that the majority of children, particularly low-income children, will not finish a higher education degree, and a very large majority will not pursue a higher education STEM career, a strong focus on higher education science implies that they will spend a large portion of their time studying curricular topics that are not relevant to their lives or future occupations, that they might be resentful of being sifted-out in their science and math classes, and that by early adolescence they will lose confidence in their capacity to participate in the STEM world (Tai et al., 2006). The pipeline model does not serve the interest of society and the government either, since the exaggerated focus on preparing children for higher education in STEM fields: a) fails to engage enough children in higher education STEM pathways b) fails to produce the necessary mid-skill STEM practitioners that the workforce also needs and that can provide young people with a decent living wage (Newman & Winston, 2016), c) fails to give children the tools to engage with STEM in their everyday lives, and d) generates negative attitudes toward science, which might explain the current resentment and suspicion by a large part of the population toward the scientific community (Atkin & black, 2007). Furthermore, it is not clear that the curricular topics being emphasized at a moment in time will be the most relevant for the workforce of the future, for example, data science and statistics (Fig 2) are arguably more valued in the workforce today than calculus, but are not as prominently represented in the curriculum. In other words, education today prepares the workforce of the future for the jobs of the past.

The problems with the pipeline model and the intense focus on higher education topics are being recognized by the education community, as expressed by Atkin and Black: “As it is realized that scientists’ science, oriented toward the painstaking construction of conceptual frameworks that explain how the world works, is of limited use to the vast majority, new ways of enabling the citizenry to comprehend and operate in a scientific and technological culture have to be sought”. With this understanding, in the later years the education community has been striving to promote project-based learning and culturally responsive education (Ladson-Billings, 2014), conceptions from which STEM and STEAM education derive, and which are associated with the values prevalent in the experiential and progressive eras. Those efforts crash against curricular subjects that are too obtuse, for example, it is hard to think of a culturally responsive and experiential way to explore the difficult concepts of wavelength or the particle-wave duality of light, which, it can be argued, is not even understood by professional physicists (Ballentine, 2014). An additional problem of these obtuse standards is that being poorly understood by teachers and curriculum developers, they are reflected in superficial activities that misinterpret the natural phenomena that they are meant to explore, and that can only be accomplished through rote memorization (Figure 2), which removes the children's agency as understanders and inquirers. Those traditional curricular topics are decontextualized, in the sense that neither children nor teachers know why they are important or how they can be applied to their lives, which deprives children of a motivation to learn them other than to continue their academic life. Studying subjects without a clear motivation, especially for students that are not driven by grades and do not aspire to pursue higher education, is tedious and hard, or, as the Sputnik era discourse often calls for: rigorous (from Latin *rigorem*, meaning stiff). The emphasis on rigor as a primary value is surprising, since there is no indication that rigorous work produces more meaningful knowledge, and on the contrary, the less meaningful the knowledge the more rigorous study it requires.

In contrast to rigor as a primary value, STEAM education offers curiosity, passion, and the aesthetic experience (Booker & Minces, 2022; Milne, 2010), values that more faithfully reflect the experience of scientists and artists, for whom rigor is secondary to the pursuit of those passions. Through its connections with the arts, STEAM education signals a way for choosing curricular topics that are personally relevant to the child. Importantly, if the community gets past their rigid expectations of what science should look and feel like, it can be understood that Thickly Authentic STEAM topics are not any less science than other traditional curricular topics. For example, understanding how objects vibrate, how microphones work, or how to read and manipulate signals is not any less science than understanding the concept of wavelength (Fig 2). And because Authentically Thick STEAM activities are contextualized in personal goals they are less prone to misinterpretation. In our example, a child needs to understand how to read and manipulate a signal to achieve their artistic goal of creating a sound composition. Through such activities, all children can engage with STEM as creators, develop agency and positive attitudes towards STEM, acquire knowledge that allows them to reinterpret their everyday environment– in our example, popular music– and gain skills that they can immediately apply, so they never need to ask “what are we doing this for?”. These experiences are directed at enriching the lives of all children, rather than the selected few that will follow a STEM higher education path, and these experiences are actually likely to increase the proportion of children that follow that path. Furthermore, the skills gained can be extended into other STEM fields that are highly valued in the workforce, as the Earsketch music coding platform (Freeman et al., 2014) or these authors' data literacy work indicate (Nagarajan et al., 2020).

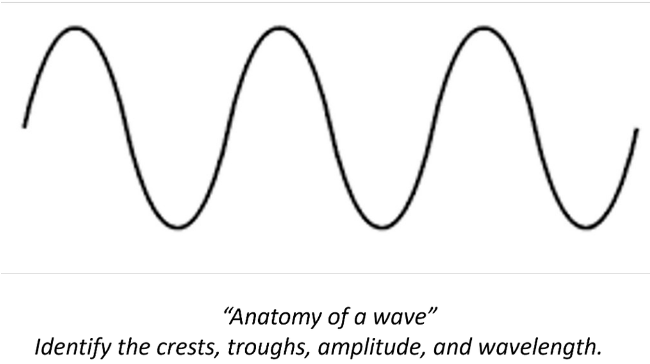

Figure 2. STEAM vs traditional schooling practices. Left, typical test given to children to assess their knowledge of waves. Note that the axes do not have labels so it is not clear what the line is representing. Teachers can administer the test and students can comply, even without understanding the meaning of the concepts. Right, children create musical compositions using a sound editor and oscilloscope (see list of relevant websites). Through this activity children can learn to measure, visualize, and manipulate signals, which are ubiquitous practices in science and engineering, and improve their data literacy (Akshay et al., 2020).

STEAM calls for rethinking the curricular topics to move them from decontextualized and impersonal to contextualized and personally relevant. Possibilities abound, as children work on woodworking projects they can learn algebra and geometry, develop their spatial intuition, explore the properties of materials and learn to design for structural stability; if they have access to laser cutters or CDC routers they can learn fabrication technologies and digital design. Importantly, they will be learning woodworking. Children can also learn electronics in the context of clothing design (Peppler, 2013), computing in the context of videogame design (Resnick & Robinson, 2017), optics in the context of photography, chemistry in the context of cooking and painting (through the creation of pigments) and, in the spirit of Leonardo, biology and geometry in the context of drawing.

The examples above point to a need to modify the academic structure to reflect project goals rather than siloed academic fields – for example introducing sound production, computer music, video game design, or woodworking classes – and to rethink the teacher workforce to include domain practitioners rather than teachers that do not have practical expertise in the fields they are teaching. Through these activities and personal interaction with practitioners, children can become aware and start exploring possible career occupations more immediately available to them after high school, such as carpentry, or that require further academic training, such as structural engineering.

This vision for education has many commonalities with vocational schooling. This is not a coincidence, since they both share the philosophy of goal-based and situated work. Mainstream schooling has a lot to learn from vocational schooling, which when implemented properly can provide mid-skill workers for the economy and has been shown to decrease school attrition and lead to good employment for young people, particularly for the many children that do not thrive in a less contextualized academic environment (Newman & Winston, 2016). As opposed to vocational education, however, this vision puts a heavier emphasis on creativity and personal meaning, and does not call for the highly specialized technical education that could limit young people's career choices.

Thickly Authentic STEAM practices also call for shifting the way students' capabilities are assessed, away from tests (Figure 2) and toward performance assessments in which children demonstrate their learning through the artifacts they create (Bland & Gareis, 2018). This shift can also allow students to create a personal portfolio which can be useful in securing future employment.

The proposals above defy the role of K12 education as a sorting mechanism for higher education. This is problematic within a system that values higher education credentials in terms of social status and in terms of economics, as higher education degrees are requisite for high-paying jobs (Baker, 2014; Collins, 2019). However, these proposals might better accompany current trends in higher education and the world of work, which have been under increasing pressure – and perhaps recognize the need – to become more inclusive of social groups traditionally underrepresented. In response to that pressure, several prestigious universities have been reevaluating their admission practices to be less reliant on traditional measures of capability (Hubler, 2020; Sandel, 2020) that favor high-income applicants; and as private companies and governmental institutions have struggled to find capable employees, they have been steadily expanding hiring practices that are less reliant on the applicants credentials than on their skills, in what is referred to as skill-based hiring (Ark, 2021; Lohr, 2022), which can be well developed through STEAM practices and well represented through the students' portfolios.

Conclusion

The school system appears to be in tension between an instrumentalist conception of education as a workforce factory and a humanistic conception that forefronts the children's well-being and intellectual development. Part of this tension arises from society's narrow views of what STEM and the arts should look like, and what are the paths necessary to get to them. The conception of STEM paths as a pipeline into higher education has deprived children of the possibility of experiencing STEM fields as fascinating and useful, alienated them from STEM, and done little to achieve its expected goal of developing the workforce. By opening the field of vision and recognizing the many ways in which children can engage creatively in STEM fields through the arts, STEAM education can harmonize that tension, engaging more diverse children in STEM paths, bringing them value and skills that they can readily use, and contributing to making their school experience more joyful.

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List of Relevant Websites

The art of innovation, BBC podcast series on the historical connections between arts and STEM https://www.bbc.co.uk/programmes/p07lxl0v

A History of Electronic Music https://ahoem.org

Online oscilloscope: www.listeningtowaves.com/oscilloscope

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