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Experiential Investigation of STEAM Projects: Art and Engineering

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Synopsis:

Schools at all levels are implementing Science, Technology, Engineering, Art, and Math (STEAM) programs, but not all share the same goals or the same outcomes. Ideally, STEAM programs foster whole-person development by improving creativity and innovation, by teaching technical concepts within a meaningful context, and by improving the balance between logical/cognitive thinking and creative thinking. This should result in both well-rounded citizens and improved problem-solving skills. In this study, a professional artist and a mechanical engineering professor collaborated on a STEAM project in order to investigate the factors that lead to STEAM projects.

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Abstract

Schools at all levels are implementing Science, Technology, Engineering, Art, and Math (STEAM) programs, but not all share the same goals or the same outcomes. Ideally, STEAM programs foster whole-person development by improving creativity and innovation, by teaching technical concepts within a meaningful context, and by improving the balance between logical/cognitive thinking and creative thinking. This should result in both well-rounded citizens and improved problem-solving skills. Teaching within a meaningful contextual framework fosters learning. Usually the goal of STEAM programs is to use the arts to provide context and motivation for science, technology and math concepts, although arts and humanities can also be taught effectively in a cross-disciplinary approach. In some cases, STEAM programs are used primarily to improve recruitment and retention in the STEM disciplines. The latter programs may lose many of the potential benefits of a broader-minded approach, and tend to perpetuate the idea that STEM disciplines are more valuable than arts and humanities.

The design process is remarkably similar for graphic design, industrial design, and engineering. While the outcomes and constraints vary significantly, the creative process itself is the same. In most engineering curricula, students are taught technical skills in depth, but are often expected to be able to develop innovative solutions to design problems on their own. Innovation and creativity are taught only sparingly in design courses. In many science curricula, even that element is missing. Yet creativity and innovation are crucial skills for any type of problem solving. Artists are trained to be creative, and many works under an equally rigorous – although very different – set of constraints. Often these constraints involve design and technical problem solving. Both artists and engineers benefit from a wholistic approach to creativity and problem solving, in which stereotypical divides between the disciplines are relaxed or eliminated. Both functions better with an understanding and appreciation of the other. The best engineering is beautiful, and the best art is well engineered.

In order to explore what a meaningful STEAM project could be, a professional artist and an engineering professor collaborated on an art installation that required contributions from both engineering and art. This exploratory, experiential approach provided both the means and the context for investigating the intersections of art and engineering. The culminating exhibition, “Spend Time with Trees” occurred in Washington DC during the summer of 2019. Attention was paid to the process of design, development, and creation, with an emphasis on learning the practices of the other profession. Results illustrate the advantages of integrating engineering and art, as well as identifying key elements that should be present in a meaningful STEAM project. Projects should be truly collaborative, requiring elements from different disciplines. Emphasis should be placed on the successful outcome of the project rather than a narrow focus on a particular set of skills. This breaks down the artificial barriers between art and engineering, allowing students to learn in a truly meaningful context.

Background

The arts and humanities are not treated the same as science, technology, engineering and math, or the STEM disciplines. They do not receive the same emphasis in our schools, nor do they receive comparable funding. During his tenure in office, President Obama consistently pushed for improved STEM education, with an ambitious program and over one billion dollars in funding.[1] He called for an "all-hands-on-deck" approach, including training an "army of teachers" to make sure "all of us are lifting up these [STEM] subjects for the respect they deserve." Ken Robinson argues that standardization leads to narrowing of curricula and an undue emphasis on STEM at the expense of arts and humanities.[2] He stresses the importance of providing a balance in all of these areas, which address different modes of intelligence and means of developing creativity. A balanced education requires a balanced curriculum. Yet the calls for STEM emphasis have not abated. In January 2020, Chaouki Abdalla, Georgia Tech Executive Vice President for research, testified before the US House of Representatives Committee on Science, Space, and Technology that the US is at risk of falling behind competitors in several technological areas due to insufficient funding and policies that discourage graduate study in the US.[3] While his comments did not explicitly exclude arts and humanities, it is clear that the emphasis is on STEM.

In response to the imbalance between arts and humanities and STEM disciplines, a new acronym simultaneously emerged: STEAM, or Science, Technology, Engineering, Art, and Math. Arguments are made for including art based on its intrinsic value, as a means of improving creativity and innovation, and as a means for motivating and inspiring students to study STEM disciplines. STEAM programs and courses are becoming more popular, and span all educational levels, from primary school to college. They also have a variety of objectives and diverse outcomes. In some cases, art and science are combined outside of any explicit STEAM program or curriculum. For example, Penn State University, Berks, recently inaugurated a general education course, PHOTO 321N, in which students learn about a variety of aesthetic issues and qualitative science concepts.[4] Objectives included integrative thinking, creative thinking, and effective communication. This course included both art students and engineering students. The authors conclude that by combining art and science, students were helped both inside and outside their disciplines. That is, engineering students learned more about fluid flow (even if they had previously taken fluid dynamics courses) as well as aesthetics and techniques of photography, while the art students learned more about photography and aesthetics while gaining understanding of fluid flows. Based on student surveys, the authors conclude that the goals were met, and that the class participants showed significantly more positive attitude shifts than either regular art or science classes. This illustrates a fairly common theme that teaching cross-disciplinary courses can improve outcomes.

Robert Root-Bernstein has shown that the most successful scientists – Nobel Prize Laureates, the US National Academy of Science members, and members of the British Royal Society – are much more likely to engage in arts and crafts at a high amateur or professional level than are scientists in general or the public at large.[5] Nobel Prize winners are 30 times more likely to practice arts avocations than members of Sigma Xi (the Scientific Research Honor Society, taken to be representative of most scientists), and National Academy of Science members are nearly three times more likely to practice arts. Root-Bernstein further makes an argument that a background in in the arts contributes to the success of scientists, and includes many statements from Nobel Laureates to illustrate this point. Interestingly, the Nobel Laureates do not have the highest IQ, nor is IQ generally related to creativity (at least at higher IQ values.) Very creative people tend to excel in both the arts and sciences. Root-Bernstein suggests that current science curricula may need to be broadened, a conclusion that has helped to drive STEAM programs.

In a thoughtful editorial, Tod Colegrove called for "creative abrasion" and "trans-disciplinary collaboration" in libraries.[6] Citing Root-Bernstein, among others, he argues that traditional organization of knowledge tends to isolate both the physical collections and the practitioners of the various disciplines. A new organizational structure that promotes collaboration across disciplines would be beneficial, as would means of fostering creativity and multiple viewpoints. Moving from STEM to STEAM by including Art increases diversity and enhances creativity. Colegrove suggests that incorporating makerspace services – that are open and visibly accessible to all – are a natural fit for trans-disciplinary collaboration, enabling interaction and engagement across the STEAM spectrum. And this leads to a richer world.

An over-reliance on standardized tests, a result of the No Child Left Behind Act, stresses memorization over problem-solving and creativity.[7] Including art in STEM education can provide media literacy, help with a balance of convergent and divergent thinking, and enhance creative problem solving skills. Creative thinking – the ability to perceive possibilities and alternatives – is often contrasted with critical thinking – the ability to question and evaluate assumptions, claims, perceptions and judgements.[8] Creative problem solving requires both. Deliberately incorporating fine arts and aesthetic considerations into engineering education may improve student learning and enhance both creativity and criticality. Arts pedagogy, such as studio-based learning is one way to do this. Connor, et. al. suggest that such experiences can enhance engineering education, and goes further to provide a "manifesto" of guidelines for incorporating studio-based learning into engineering courses.[9]

During the last decade, there has been a growing acceptance for adding Art to STEM. Robelen notes several programs combining art and science or engineering, including the ArtScience prize, the Philadelphia Arts in Education Partnership (helping elementary school students understand abstract math and science concepts through art projects), and the National Science Foundation's The Art of Science program.[10] A California grant for linking arts and science, aimed at upper elementary grade students, and a program at The Wolf Trap Foundations for the Performing Arts that blends STEM with the arts are further examples. However, there are contrarian voices. Jolly looked at both proponents and opponents of adding Art to STEM, at least at a programmatic level.[11] She notes that STEM is a specific program established for a specific purpose, the purpose being to integrate and apply math and science to create solutions to real-world problems. Those opposed to adding Art to STEM may consider that STEM programs inherently include art in the context of product design, language art in the context of communication, and social studies/history in the context of engineering design challenges. Some also claim that including art could dilute the mission of STEM. On the arts side, some object to STEAM because it seems to implicitly value art only for how it can improve STEM education, and not for its own sake. (The latter could be termed *STEAM for STEM*, and is a prevalent theme in much of the literature.) STEAM is most effective at the strongest intersections of art and STEM, such as design, performing arts, and creative planning. Jolly concludes her article with a quote from Dr. Howard Gardner: "I don't have strong views about whether arts should become a part of STEM or be self-standing. What is important is that every human being deserves to learn about the arts and humanities, just as each person should be cognizant of the sciences." This is a more holistic viewpoint, and perhaps a more important one, than STEAM for STEM.

There are many examples of STEAM for STEM, integrating art into engineering and science courses with the object of improving the STEM outcomes. Drexel University hosts a Summer Music Technology program for rising high-school freshmen and sophomores.[12] Students explore music and the science of sound, as well as audio technology. This is a good blend of science and art, with the explicit purpose of increasing interest in STEM-related fields. Bill Gates, while not promoting any particular STEAM program, has called for a passion for learning in all fields, including art, technology, and science.[13] He is inspired by Leonardo Da Vinci, an engineer/artist whose curiosity and creativity are well known. Patricia Caratozzolo and colleagues provided engineering students with an art appreciation course with the goal of improving engineering creativity.[14] They showed that creative thinking in engineering students can be improved by using design thinking and art design methodologies. Interestingly, Caratozzolo perpetuates the common, but unfounded idea that engineering design is fundamentally different from artistic design, because the latter is "free in expression". The similarities between the artistic design process and the engineering design process are addressed later in this paper. Unfortunately, STEAM is often used as a cover for what is really just a STEM program. Wang and Frye studied how middle school girls' attitudes toward STEM changed over the course of a summer STEAM camp.[15] While the results were positive with respect to improved attitudes, there was apparently very little art during the two-week camp.

In higher education, one STEAM supportive success story is the MIT Media Lab and its cross disciplinary collaborative graduate programs. Media Lab alumni and researchers excel in careers where they bring their unique skills and insights to industry or become independent designers, artists, inventors, and consultants.

Beyond STEAM as an educational program, there is considerable evidence to show the real life connections between art and engineering. Aesthetics is a vital component of engineering design, and much art requires engineering. Anish Kapoor is an artist known for very large architectural installations, such as "Cloud Gate" in Chicago or "Orbit" in London. Neil Dodgson has analyzed several of Kapoor's works from an engineering standpoint, and highlights the very challenging technical difficulties of creating works such as Taratantara (1999), Leviathan (2011), and Svayambh (2007).[16] These works depend on good engineering, but Kapoor himself is not an engineer. The successful outcomes depend on collaboration of artist and engineers.

Many professional fine artists employ a "workshop" model—employing whole workforces of collaborators, known as "assistants," (e.g., notably Jeff Koons and Olafur Eliasson each employ around 150 people) whose responsibilities range from actual artmaking to engineering to design to promotion. In fact, there is a great debate within the art community as to the workshop use of assistants (a word specifically employed to minimize the idea of collaboration) versus solo artistic creation. It is, however, an example of the interrelated nature of creation. [17]

Of course, industries such as industrial design and textile design, as well as architecture naturally connect artistic design and engineering. For example, Wang, et. al. used fractal graphics generated in MATLAB to produce novel and artistic patterns for scarves.[18] Architectural examples abound, but the atrium for Duke University's Nasher Museum of Art is a nice example of innovative structural engineering in conjunction with innovative aesthetic design.[19] As part of an art museum, aesthetics and artistic design are particularly appropriate. Scientific research can also lead to art, and the tools of science have often been turned to artistic ends. Antigoni Avramouli and colleagues use microscopy – traditionally a means of acquiring and analyzing scientific data – to create art.[20] This raises interesting questions about the relationship of technology and art. Art has always used advanced technology for creating images and objects that move us emotionally.

Engineering Design and Artistic Design

Design is an oft-used but ambiguous term that implies the creation of something new. The term is used in many seemingly diverse fields and disciplines, such as graphic design, fashion design, and engineering design. John Heskett argues that the capacity to design is at the core of what it means to be human, and provides the following definition: "the human capacity to shape and make our environment in ways without precedent in nature, to serve our needs and give meaning to our lives."[21] This definition is equally applicable to engineering, industrial design, graphic design, and fine art. It implies creation or at least the evolution of something new. It also implies that everyone has the capacity to create, and there is a commonality, a human connection, across the design spectrum. There is an ongoing debate within fine arts as to the role of design and whether the criteria necessary to determine an artwork's success includes design or even aesthetics. For our purposes, we presumed the inherent intention of design in creating artwork.

The creative process of design is remarkably similar across disciplines, whether for engineering or artistic purposes. This is in contrast to biases on the part of both artists and engineers. Despite the fact that many talented engineers are also accomplished musicians, writers, and artists, scientists and engineers are apt to consider the creation of art as either unimportant or at least easier than technical design. The perception that artistic design is free of constraints, and therefore not rational or rigorous seems to be persistent in certain circles. Indeed, this bias crops up in the literature, as noted above. Artistic design in its broadest sense encompasses the creation of both objects d'art – objects whose sole function is to elicit an emotional response – and functional objects, but in all cases aesthetics is a vital element. Engineering or technical design involves the creation of systems, components, or software. Both consist of synthesizing something new, and both require creativity. Table 1 compares the design processes described in a graphics design text by Maggie Macnab[22] and engineering design texts by George Deiter[23] and Shigley and Mischke[24]. The methods, techniques and outcomes used by the graphic artist (whom we presume to represent fine art as well) and the engineer are quite different, but the overall process of creating something new is very similar. Both involve defining what is to be done, research, conceptualization, evaluation, iteration, and presentation/communication of the final product.

Table 1Comparison of Design Process Steps

Mcnab, 2012	Deiter, 2000	Shigley & Mischke
	Identification of Customer needs	Recognition of Need
Design Scope Define Boundaries and parameters	Problem definition	Definition of the Problem
Investigate & Research	Gathering Information	
Conceptualize the Design	Conceptionalization	Synthesis
Rough it Out	Concept Selection	Analysis & Optimization
Test the Design Internally	Refinement of PDS	Evaluation
Comprehensive Design Review	Design Review	
Present the Design	Embodiement Design Product Architecture Configuration Design Parametric Design	Presentation
Finalize the Design	Detail Design	

Despite the similarities in the overall design process, engineers and scientists are taught to approach problems in a very different manner than designers and artists. Engineers are taught technical skills in math, science, and engineering science, where they learn to break complex problems into smaller, tractable problems and solve them. Unlike pure science students, who are similarly taught, engineering students do study design. However, this usually involves a few lectures on the design process, learning tools such how to operate CAD, and then turning students loose to design on their own, perhaps with technical advice on the efficacy of the proposed solution. The emphasis is on technical accuracy rather than creativity. This is perhaps odd, considering how often the word "innovation" is used to describe engineering programs. And despite some mention of aesthetics, there is essentially nothing in the typical science or engineering curricula to teach aesthetic principles. Artists and designers learn the tools and methods of their respective disciplines, and must work under a different, but still rigorous, set of constraints. A culture of creativity is intentionally encouraged and fostered, and aesthetics may be a crucial element; however, what is primarily taught in school is how to master the tools and media.

It was not until the industrial revolution was in full swing that the disciplines of science and engineering emerged independently from the arts. As disciplines have become more specialized, they have also become more isolated. Consider Leonardo da Vinci, who called himself an engineer but who is now best remembered for his art. In his day, the boundaries between art, science, and engineering were fluid, if they existed at all. It is impossible to imagine that Leonardo could have accomplished what he did in art, engineering, or science had he not been seamlessly involved in all three. The links between art, science, and engineering are strong, and the connections deep. A math professor, when asked about the criteria for judging a PhD dissertation replied that the two criteria are originality and aesthetics – that is, creativity and beauty.[25] Aesthetics is important in science and engineering, and it is not unusual for art to require engineering. Learning to create and judge aesthetics along a more common educational core would be beneficial to all.

Collaboration Experience

In order to explore what it means to combine art and engineering, a professional artist (Arkin) and a mechanical engineering professor (Archibald) collaborated on an immersive art installation involving both art and engineering. The resulting show, “Spend Time with Trees,” was presented at an art gallery in Washington DC in the summer of 2019. Archibald took a sabbatical during the spring 2019 semester in order to complete the project. During the process, both learned something of the methods and practices of the other, and strove to understand the elements of a good collaborative project joining art and engineering. A fundamental question was: What elements are necessary to ensure a STEAM project is valuable to all participants?

The broad goals for the project were to explore what it means to work together as an artist and an engineer, and to gain general insight into similar collaborative projects. What can the engineer bring to the project, and what can he learn from it? What does the artist bring to the project, and what can she learn from it? How is the result something greater than either could accomplish on their own? What was within each individual practice of interest to the other? When the boundaries between disciplines are lowered or eliminated, there is always the possibility of an exciting synergy developing.

Initially, the specific project was undefined although an early interest was in the use of 3D fabrication and/or other technology to create some of the elements. During meetings between January and March of 2019, the project concept evolved from a vague idea of a public art work to the specifics of an art installation in a specific gallery. An art installation differs from a plain exhibition in that it is a distinct genre usually site-specific, conceptual, dimensional, and designed to transform a space rather than a collection of objects. Installations often require audience participation to activate. As it is “on exhibit,” an installation is also referred to as an exhibition. The theme of trees and forests emerged as an area of common interest and passion for both collaborators. As the specifics began to come into focus, several criteria emerged for assessing a valid project. The project must be:

1. Consistent with the ethical worldview of both Arkin and Archibald
2. Truly collaborative – each brings something important to the project
3. Meaningful in some sense, perhaps spiritual
4. Beneficent – bringing some good to the world
5. Multi-sensory
6. Accessible (wheelchairs, etc.)

The last item – accessibility – was deemed important for both. The gallery hosting the exhibit is owned by a non-profit that provides resources for people with disabilities to work as professional artists.

Methods

The methods used were tailored for the specific project, and included in-person and telephone discussions, visits (together and singly) to art museums and exhibits, creating exploratory artworks (both Archibald and Arkin separately), collaborative design of the specific elements, and documentation/evaluation. Early in the process, before any specifics were known, Arkin and Archibald visited galleries and museums to discuss art, meaning in art, and the elements of art that most engaged each as individuals. They also addressed specific questions that the Arkin had on what constituted engineering. Aspects of both disciplines were found in each individual practice. This was particularly beneficial to Archibald, who kept notes from the museums and developed a scale for evaluating and assessing art with the goal of discovering the elements that were most desirable in his own creation. Early discussions involved brainstorming, reflections on art, and searches for common interests. During this process, each respected, trusted, and listened to the other, key elements of successful collaboration. As the project developed, discussions shifted, becoming progressively more specific as the different elements were designed.

In the first three months of the project, Archibald spent much time on reading and studying topics in creativity, industrial design, and graphic design, as well as creating several exploratory art works on his own. These proved to be invaluable exercises, introducing him to key ideas and challenges in artistic design. They provided a deeper understanding of the elements involved, the importance of meaning, and the significance of craftsmanship. The exploratory art works included metal and wood sculptures and a mobile. He also explored poetry, writing one poem per day for a month. During that time, Arkin explored different media and concepts related to the topic as it developed, in addition to creating some prototypes to be explored (and/or discarded) as the project progressed. From an explanation of the broad scope of what defines art, she suggested that documenting bread-making weekly could be considered an endurance performance (only Archibald undertook this).

Collaboration on the installation project dominated the work over the next few months. Arkin and Archibald met frequently by phone and when possible in person (living 300 miles apart precluded frequent in-person meetings). Additionally, work was shared via an on-line shared journal and shared file folders. Some pieces were made by each collaborator and two pieces were made jointly. The work progressed through stages very similar to those in Table 1, starting with defining the idea, exploring and researching options, developing concepts, constructing and evaluating concepts, and finally installing the work in the gallery, reviewing it, and sharing the installation during opening, closing and artist talk events.

Final Outcome

The installation, entitled "Spend Time with Trees," was intended to evoke the feelings of being in a forest. It was designed to be three-dimensional, immersive, and multi-sensory. Entering the gallery, a visitor walked over a thin pad that actuated sounds intended to be reminiscent of croaking frogs and woodpeckers. This was the first of two "Footfall Whispers" created by Archibald. In keeping with the natural theme, it was determined early that all sounds and actions would be accomplished mechanically, and powered solely by the visitors themselves. Hence, the actuators were mechanical. Compact mechanical actuators (designed by Archibald with components printed in the 3D lab) operated produced sounds when stepped on. Designing the actuator pad in compliance with ADA standards (one of the goals of the project) was a technical challenge, solved using a compact cam mechanism. Also, the actuator "symphony of sounds" had to be installed nearby.

After passing over the entrance pad, a visitor would enter "Bamboo Showers," a collection of groups of bamboo bead strings, suspended from 24 inch squares of hardware cloth in frames and clustered into columns reminiscent of tree boles created by Arkin. Visitors could walk among and through the "trunks," feeling the smooth beads and hearing their soft swish and clatter. In the center of the groupings were three tree stumps, placed for sitting and meditation.

The visitor next walked around three platforms of tree branches emerging vertically, called "Grove Cross-Sections" that was created jointly. The most ephemeral of the works (it was created on site and destroyed afterwards), this piece was likely the most successful portion of the exhibition as it was 100% collaborative, highly aesthetic, and fully realized as conceived and designed. Essential oils were used on the Grove Cross-Sections to provide a mild balsam scent as visitors passed. Visitors then passed by two paintings of forests provided by another artist that we selected to round out the experience (Ellen Sinel).

The next component was "Trunk Copse," suspended paper "trunks" made of recycled financial documents. Arkin pulped old financial documents and created new handmade paper. The paper was then shaped into "logs" some of which were suspended to mirror the pieces comprising the bamboo forest, and others created as trunks to be dispersed within the installation.

A second sound pad "Footfall Whispers" actuated wooden croaking frogs. It was placed before the joint piece "Boughs Cast Shadow," comprised of one hundred oak leaves made with a 3D printer suspended in three clusters and lighted so as to cast shadows on the wall. Both the leaves of "Boughs Cast Shadow" and the paper trunks of "Trunk Copse" would sway and move due to light breezes in the room to mirror and unify to the bamboo columns at the entry.

"Forest Glider" was a glider bench designed by Archibald made of oak trunks and manila rope. A visitor could sit and gently glide while contemplating "Bark Swatches," a dozen photographs of closely examined tree bark by Arkin mounted on the wall. The photographs, taken from trees around the world, were printed on plywood in an 8x10" format (close in size to an 8 ½" x 11" sheet of paper), providing a three-dimensional aspect that was quite remarkable.

Additionally, there were branches and recycled paper trunks placed artistically in other areas of the gallery along with sound-making toys that could be actuated by visitors.

Assessment

Assessment of the collaborative project included two tasks: evaluating the effectiveness of the installation and assessing what we learned from the collaboration. The installation was apparently enjoyed by visitors, some of whom found it quite moving. The gallery staff reported several visitors were visibly moved, in some cases to tears, by the exhibit. The mechanical acoustic elements (the sound pads) produced sounds that were less contemplative but more playful than originally intended. Not everything worked as planned, so we had to be flexible, and the process of creating the actual on-site installation and joint works took a solid week. However, the artists enjoyed seeing the joy both children and adults experienced when stepping on the pads or passing through the Bamboo Showers.

The installation project was evaluated with respect to the previously defined goals. Table 2 summarizes the goals and whether each was realized. Overall, all goals were realized.

Table 2 Assessment: Were goals realized?

Desired/Required Element	Realization
1. Consistent with artists' ethical worldview	Realized. Both value trees, forests and nature, and value beauty. The installation honors those values. (We discovered our joint love of forests early in our brainstorming sessions, and it soon came to be central to our thinking.)
2. Truly collaborative -- each brings something to the project	Realized. Artist and engineer contributed significantly, and complemented each other's skills and talents. Each respected the other's ideas and valued the other's contributions.
3. Meaningful in some sense, perhaps spiritual	This is more subjective, but the we believe it was realized. The final result was more playful and less contemplative than the initial vision, but meaning can be found in play as well as contemplation. The installation clearly reflected the artist's common ideals (see 1 above). (It is, of course, difficult to assess meaning for those experiencing the installation.)
4. Beneficent	Realized. Trees are worthy of our respect and awe. The subject matter may motivate visitors to be more aware of the importance of forests in an era of climate change and de-forestation. Subjectively, the artists believe there is beauty in the installation, and that beauty is good and valuable.
5. Multi-sensory	Realized. The exhibit included visuals, tactile surfaces (bamboo, rough wood), sounds (bamboo, bird calls, sound pads) and smells (balsam & other oils.)
6. Accessible (wheelchairs, etc.)	Realized. People with a variety of disabilities could pass through and enjoy elements of the show. A man in a wheelchair was able to demonstrate this prior to the show opening.

Lessons Learned

One of the overarching goals of this collaboration was to learn by experience elements that are most important for successful collaborative STEAM projects. Five key elements were identified – collaboration, knowledge, value of each team member, communication, and focus. While in this project, the team of artist and engineer are each accomplished at the professional level in their respective fields, these key elements should be generalizable to all levels of STEAM projects. There was a great deal of amplification of skills that was also accomplished and should not be overlooked: whereby each collaborator was able to accomplish more within the team than they might have alone. Most are related to collaboration and teamwork, as meaningful STEAM projects are almost always collaborative and trans-disciplinary. Implementation in some settings may require re-thinking of how groups are formed and projects defined. Groups that are too homogenous – for example a group of mechanical engineering sophomores – will lack the breadth and depth and difference of perspective that are so important for creative trans-disciplinary projects. The five key elements are:

1. Collaboration: Collaboration is much more than cooperation. In the words of Randy Nelson, collaboration is an amplification of what team members could do individually.[26] Two aspects of collaboration are particularly important: accepting every contribution without criticism, and always making your partner(s) look good. Accepting every contribution means reacting to an idea – no matter how bizarre or odd – by asking how the idea can be used to push the project further. Making your partners look good fosters confidence and trust, opening the door to potential creative and novel solutions.
2. Knowledge: Knowledge is crucial for developing creative, effective solutions. Ideally, team members should have both depth of knowledge within their respective specialties and breadth of knowledge. Further, the knowledge sets of the various team members should be complementary. Exposure to new ideas – the knowledge domain of other disciplines, for example – can be the crucial spark that leads to creative innovation.
3. Value of each team member: Each team member should bring value to the project. Each should feel that their contribution is valued by all team members. With a supportive team that values and respects all members, the likelihood that everyone can contribute is increased. Often, if a person is valued, their value to the team increases.
4. Communication: Communication across various media is crucial for any collaborative STEAM project. This implies more than competence in speaking, listening, writing, and ability to create graphic images. Effective communication requires a fundamental understanding of each other's vocabulary. Often, the same word has a different meaning, and the same concept a different word. But concepts are rarely identical, and understanding subtle differences due to a different perspective is crucial for creative collaboration. Trans-disciplinary communication requires an eagerness to learn, a willingness to ask, and an ability to carefully listen.
5. Focus: The focus of each individual should be on the project outcome, not on their own field, their own vision, or their own usual work habits. If a team member makes contributions outside of their field, that is fine – the goal is a successful outcome.

Conclusion

An artist and an engineer collaborated on an art installation that required both engineering and artistic skills. The project was an experiential study on integrating A (for Art) with STEM disciplines, or STEAM. The results show the benefit of trans-disciplinary collaborative projects. Such projects can be beneficial to both artists and STEM practitioners, and can often lead to creative insights that otherwise would be missed. Ideal STEAM projects involve meaningful contributions from both the arts and the technical disciplines. All voices should be heard and respected. The project should not promote or value one field over the others, but should strive to identify the intersections between disciplines that leads to new and deeper insights. Emphasis should be on the project outcome rather than a narrow focus on a particular set of skills or knowledge.

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