Arts Problem-Solving for Engineering Problem-Solving (APS4EPS): Multi-Modality Skill Building - P-12, College, and the Impact Beyond

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1. Introduction

Improving engineering education is a goal shared by engineering educators, accrediting bodies, government, and industry. Naturally, there are many approaches to improving engineering education, and many aspects of engineering education that require attention and effort. The present paper connects one recently popular approach with a specific aspect of engineering that is a critical part of making engineering education more relevant to engineering practice.

Design is a key component of engineering. Curricula that make it possible for students to experience one or more major design projects as part of their junior or senior years are, likewise, critical to successful undergraduate engineering education. These projects emulate the work of engineers in industry in that they involve trade-offs, cost constraints, interdisciplinarity, ambiguity (open-ended descriptions and practical specs), and multiple solutions requiring flexibility on the part of designers. As such, they typically entail teamwork, rely on clear and effective communication (with a sponsoring company in addition to within the student team itself), and require the ability to apply a variety of material from across the curriculum. The stark difference between such a design experience and the well-structured nature of textbook problems that students spend an appreciable portion of their studies focused on solving is at the core of a distinction that we wish to draw attention to between ‘problem-solving’ and the solving of problems.

According to a joint executive report from the National Science Foundation (NSF) and the National Endowment for the Arts (NEA), student skills in engineering problem-solving (specifically in electrical engineering and computer science) are in dire need of a boost. The report states that “undergraduate and graduate students who study electrical engineering and computer science lack the ability or self-efficacy to create new ideas and innovations that stretch beyond rote classroom exercises”[1].

Other high-profile reports agree: The National Academy of Engineering lamented in 2004 that “engineering students are not fully comfortable thinking creatively[2].

As discussed further in that joint report—for example: “skill development and speculative artistic inquiry often work jointly to result in more productive student endeavors”[3]—and elaborated in the present paper, when it comes to engineering-student performance in design under constraint, a significant improvement can be drawn from engagement in an unexpected field: the arts.

We present an evidence-based argument for improving student success in engineering problem-solving through substantive and progressive engagement with arts problem-solving. The rationale for this argument, detailed below, rests on the observations that problem-solving is not limited to engineering and that problem-solving and design under constraint are equally central to the arts.

The argument proceeds by answering questions such as the following.

- What is problem-solving?
- What is the role of problem-solving in engineering design?
- Is there problem-solving in the arts?
- If so, is arts problem-solving such that it entails design under constraint?
- Is there evidence for the transfer of skills between the arts and the STEM fields?
- Is there evidence for the transfer of problem-solving skills between the arts and the STEM fields?
- If so, can a testable hypothesis and experimental design be formulated to study the transfer of problem-solving skills from the arts to engineering?

We will show not only that problem-solving and design under constraint are key components of art-making, but also that strong (although general) quantitative, causal connections have been drawn by industry, government, and academic sources between arts engagement and success in engineering and the sciences. We then take the natural next step by proposing to test the hypothesis that problem-solving in design under constraint is a transferrable skill with the potential to augment engineering students' problem-solving ability if practiced in multiple domains rather than only (and seldom) in the engineering domain.

The literature review presented here is intended to form the basis for a long-term pedagogical study on the impact of substantive and progressive engagement in an art practice on students' problem-solving effectiveness in engineering design.

To measure this impact, we propose a long-term engineering–arts partnership, extensive educative assessment and data analysis, a joint curriculum, and scholarships to help engineering students engage substantially in an art form.

2. Problem-Solving

We find it necessary to first answer the question of what problem-solving is in the context of engineering, and how it is different from solving problems.

a. Problem-Solving versus Solving Problems

The solving of textbook problems is different enough in nature from problem-solving to have resulted in surprising pronouncements such as the following: "learning to solve problems is too seldom required in formal educational settings" and "students are rarely, if ever, required to solve meaningful problems"[4].

Fortunately for most engineering programs at the college level, students *are* expected to solve ill-structured or ill-defined practical problems in engineering education. However, this typically occurs once in the fourth year. At some—few—programs or institutions, a third-year design projects is required as well.

Practical class projects found throughout the more hands-on undergraduate curricula nonetheless tend to be smaller in scope and rarely ill-structured or open-ended. The fourth-year design project is most often the only encounter with industry-type problem-solving outside of internships for most engineering students at the undergraduate level. It is in such a project that most engineering programs ensure that *all* undergraduates have at least one open-ended problem-solving experience prior to graduation.

In addition to being open-ended and ill-structured, such a *design* process involves the identification of resources, strategies, constraints, risks, and trade-offs for the ultimate aim of creating an artifact.

To fully clarify the difference between problem-solving and the solving of problems in this context, we start with a useful and relevant definition of the term ‘problem’. Jonassen defines a problem as an unknown that has two attributes, and later adds the aspect of representation[5] to these two attributes for a total of three characteristics that allow us to identify and categorize problems.

The first distinguishing attribute of what a problem is has to do with the “difference between a goal state and a current state”[6]. This means that a problem exists when a goal state has not been reached.

The second attribute is the perceived value in finding a solution (Ibid.). A problem exists when there is value in reaching a goal state.

The third attribute is problem representation[7], and is the strongest distinguishing factor between ‘problem-solving’ and ‘the solving of problems’. We will address this in detail below.

The objects of both ‘problem-solving’ and ‘the solving of problems’ have these three components, but the nature of the components differ. In engineering problem-solving (as well as in the arts), the goal state is a tangible product, an artifact, not solely a concept or numerical calculation. Likewise, the perceived value in finding a solution in ‘problem-solving’ is practical in nature both in engineering (social or financial) and in the arts (social or cultural), whereas in ‘the solving of problems’, the perceived value is developmental or intellectual—it is theoretical rather than practical.

This distinction parallels that between innovation and creativity. Levitt famously asserted that neither ideation nor creativity are synonyms for innovation[8], but that innovation is the following up of ideation with implementation (Ibid.). It is due to the “infinitely more difficult process of being innovationist in the concrete”[9] that the arts share with engineering both the insufficiency of creativity and the central role of problem-solving. As Levitt notes, “[i]deas do not implement themselves – neither in business nor in art”[10]. Since the practice of engineering almost always exists within the realm of business, and both engineering and the arts require the implementation (not just the conceptualization) of artifacts, we see that both enterprises must rely on problem-solving, which can now be defined as the identification of resources, strategies, constraints, risks, and trade-offs for meeting an open-ended, multi-solution spec in the presence of ambiguity and variability, through the process of design under constraint.

Problem representation diverges even more strongly between practical and theoretical problems. The object of what we here call 'problem-solving' carries greater ambiguity and variability in both the problem definition and in acceptable solutions, and "requires the problem solver to disambiguate important from irrelevant information[11]. In contrast, while 'the solving of problems' may also require some degree of disambiguation, exam and homework problems typically provide all the information needed to arrive at a solution. Between coursework coverage and the problem statement, the only ambiguity usually is in the possible inclusion of extra information. This type of problem rarely requires even short-term independent learning beyond the course material. Moreover, these problems feature very little ambiguity and variability; the relevant theoretical knowledge is readily identifiable, and there is usually one correct outcome.

The contrast between these two problem types, the different nature of their three attributes, is summarized by Jonassen's distinction of *structuredness* (with Mayer and Wittrock's related terminology in parentheses)[12]. In this view, ill-structured (ill-defined) problems "possess problem elements that are unknown or not known with any degree of confidence (Wood, 1983)"; "possess multiple solutions, solution paths, or no solutions at all (Kitchner, 1983)"; feature "uncertainty about which concepts, rules, and principles are necessary"; and "are … interpersonal activities (Meacham & Emont, 1989)"[13].

Based on these characteristics of the attributes of what constitutes a problem, the distinction between 'problem-solving' and 'the solving of problems' (as typical in homework problems) lies in the process of *design under constraint* involved in what we are here calling 'problem-solving'.

We can now define 'problem-solving' to mean *the identification of resources, strategies, constraints, risks, and trade-offs for meeting an open-ended, multi-solution spec in the presence of ambiguity and variability, through the process of design under constraint*.

b. Problem-Finding as a Subset of Problem-Solving in Engineering Careers

Given the highly engineering-specific definition above, the question arises as to whether the role and prominence of problem-solving in the arts can be pertinent to engineering education or not.

To address this question, consider LaBanca and Ritchie's notion of *problem finding*"[14], which they define as "setting objectives, defining purposes, deciding what is interesting, … determining what to study [and] recognizing limitations of resources, expertise, materials, and access to individuals' time"[15].

Due to its concern with *setting* objectives, *finding* research questions, and *allocating* resources, this type of problem-solving is broader and more open-ended than even the activities likely to be required of early-career engineers. It is more typical of the challenges faced by senior engineers, engineering management, and engineering researchers. It is also highly typical of problem-solving as encountered in the arts where the realm of purpose and the challenge of limited resources figure at least as centrally as they do in engineering.

Hence, arts problem-solving, with its focus on resources and purpose, is in an even closer relationship to later-career, more open-ended engineering problem-solving than to early-career engineering experiences. To ensure that an arts problem-solving experience could be beneficial to engineering students in the short term as well as the long term, we must, then, examine and compare the roles problem-solving plays in both engineering and the arts.

c. The Role of Problem-Solving in Engineering

Problem-solving has a central role in engineering because engineering, in the final analysis, is about design under constraint. To appreciate why 'problem-solving' is central to engineering design, consider the relationship between engineering and science.

There is an outgroup-homogeneity effect in non-engineer/non-scientist observers' perception of the fields that make up STEM. (Perhaps, this has even played some role in the fact that the acronym was devised and has become so widely used.) From a superficial point of view, science, technology, engineering, and mathematics all seem very much alike. An outsider might even wonder why there are different names for them. Those of us in these fields, however, certainly have various ideas of what the differences are. In order to focus on the role of problem-solving in engineering design, and its close relationship to problem-solving in the arts, let's consider one possible way to distinguish between science and engineering.

The claim that science is all about discovery and that engineering is all about invention may be overly simplistic and outdated. Such a clear-cut distinction is no longer the (entire) practical truth. In looking to the year 2020, the National Academy of Engineering has considered scenarios in which "engineers will exploit new science to develop technologies that benefit humankind, [and] create new technologies de novo that demand new science to fully understand them."[16]

On the other hand, even today many scientists develop, innovate, invent, and design, sometimes for the purposes of their own scientific work—in the service of discovery—and sometimes as the final product of their work. The science of chemistry is perhaps the clearest example of creative, innovative science. Physics, in the creation of abstract hypotheses, and biology, in the common practice of creating microorganism by the billions even in undergraduate labs, have also moved from the domain of observing and explaining, into the creative domain of 'making'. Likewise, engineers in academia as well as corporate and government labs carry out primary research, discovering the principles underlying complex artificial systems[17]. The line has been blurred. Nonetheless, for the typical engineer at a company and the typical scientist at a research lab, Billington's distinction that "[s]cience is discovery[;] engineering is design" restated as "[s]cientists study the natural [while] engineers create the artificial"[18] still stands in the majority of cases.

In creating the artificial, engineers design products that are based on the findings of science, but which must function in the realm of human society. The former relationship through the findings of science is the close connection between science and engineering that is clear even to those with a superficial understanding.

It is the latter—the relationship between engineering and society—which necessitates that engineers have sufficient appreciation of the offerings of the social sciences and the humanities—"a broader, holistic perspective"[19]—which reveal the complex, emergent relationships critical to the success of the engineering enterprise. The physical sciences govern and guide where engineering products come from. The humanities and social sciences, on the other hand, attempt to reveal and explain where engineering products end up: how they are used, understood, misused, misunderstood; how they affect natural processes; and even how they are bent into unexpected roles by unpredictable human agents.

We have argued here for a certain commonality between engineering and the arts that requires recognizing the difference between engineering and science. It is also important not to take this too far: Although engineering and science, on first analysis, may differ in their emphasis on "making" (and the arts match engineering in this respect), we must continue to recognize the conceptual and foundational connection between science and engineering. This, too, helps identify the role that arts education can play in engineering education, by way of the wealth of studies that point to ideation gains in the sciences through engagement in the arts.

As a result of these two connections, the arts have the ability to benefit engineering both in the foundational stages (through the connection of engineering to the sciences, the latter of which, as we will see, are enhanced by engagement in the arts) and in the implementation stages (through the direct design connection of engineering to the arts).

Undergraduate engineering education emphasizes and incorporates the guiding and governing physical sciences. On the other hand, for the most part, it makes insufficient use of the fields that strive to explain how humans, technology, and nature interact. While much has been written about and done about increasing the role that the liberal arts play in engineering education[20 21 22], the humanities field with the most to contribute to engineering *design* (due to its design-under-constraint approach and the prominence of problem-solving in its practice) has been mostly overlooked.

The arts go beyond the need for engineers to be well-rounded individuals who have an appreciation for another kind of beauty. They provide a parallel avenue for problem-solving practice and development.

3. Problem-Solving in the Arts

a. Evidence for Problem-Solving in the Arts

Bowden, writing about art and design, emphasizes the role of problem-solving in art ("in which the outcome is not predetermined"[23]), and lists as essential to artistic learning the elements "intuitive leaps, … the testing of hypotheses, and … the risk of failure" (Ibid.). He gives examples of art-class projects that are almost identical to undergraduate engineering challenges like the concrete canoe.

The existence of problem-solving in arts curricula is also attested to in Glass *et al.*'s 2013 article on Universal Design for Learning[24] which discusses the contributions of an arts education to such engineering-critical soft skills as "the ability to respond to variability"[25], "finding patterns and connections, drawing inferences, … solving problems"[26], and being able to generate a multitude of ideas[27]. These claims are echoed by Louisiana Tech's Gullat who argues for the role of an arts education in making students positively disposed to dealing with ambiguity, multiple perspectives (as engineers must face in evaluating design trade-offs), and multiple solutions[28]. Gullat then provides a summary of research, listing improvements in visualization, communication, collaboration, “spatial and logical mathematical reasoning,” and risk-taking as some of the benefits of arts education[29].

The prime example of problem-solving in the arts, however, comes from Bryant who focuses on the relevance of artistic design to high-tech innovation. Once again, idea forming, sensory experiences, and pattern recognition[30] are presented as key characteristics of the “21st-Century art room” (Ibid.). The article details several “creative problem-solving strategies”[31] in the arts through numerous case studies[32], and links such experiences to the skills sought by “companies such as 3M, Google, [eB]ay, and Amazon (Gardner, 2006)”[33] Bryant defines “creative problem-solving strategies”[34] as “techniques that offer multiple ways and angles of considering a problem[,] from which an optimal solution may be selected” (Ibid.).

Bryant also synthesizes a definition of creativity that forms a direct link between art-making and innovation, by means of problem-solving in design within constraint. According to this definition, creativity is the “use of knowledge, imagination, and judgment within constraints of an environment and its resources (Slocombe, 2000) in order to solve problems in an innovative … manner (Kaufman & Sternberg, 2007).”[35]

In her Master of Science thesis, Dame-Seidler has investigated the use of “Creative Problem Solving (CPS)” tools, namely, specific techniques called “Stick ‘Em Up,” “Forced Connections,” “Visual Connections,” “Scamper,” and “Hit–Cluster–Restate Highlighting.” One clear example of the role of problem-solving in the arts shows up in the technical difficulties faced by two participants in the 10th session: “How to fix gradation?”[36] and “How to not smudge the oil pastel?” (Ibid.), respectively. These are examples of the types of physical (physics-based) technical difficulties faced by artists and art students: The painter has a vision of what they want to portray, and perhaps more importantly, how they want to portray it. However, the physical substances used and the way they are combined to give certain visual and textural effects impose limitations, much like constraints in engineering design. While Dame-Seidler’s emphasis is on specific problem-solving tools like “Scamper,” it is clear that her work has addressed, with her participants, the solutions to these design challenges.

Coming from a broader perspective, an article reporting on the experiences of an art-education foundation in San Francisco identifies problem-solving as the unifying aspect of art, mathematics, engineering, and science[37]. The author observes that problem-solving skills follow from the development of mastery[38] in both the arts and in the sciences[39]. For mastery to manifest itself, two elements seem to be required: dexterity and perseverance[40]. Dexterity is essential for artists because it is a key component of the ability to play an instrument, manipulate raw materials in pottery, sculpture, or painting, and the use of technological tools in the high-tech arts. Likewise, dexterity is also a necessary skill for engineers, though this may not be obvious. Engineers are primarily high-level thinkers, but in the competition for best time-to-market, there are occasions when even a design engineer must engage in hands-on activities typically associated with technicians: soldering, de-soldering, taking measurements, carrying out diagnostics, or making repairs. In fact, the dexterity to carry out such manual tasks, when necessary, informs an engineer's design practice by contributing first-hand knowledge of the physical facets of work of technologists downstream from the designer. (Further relevant aspects, primarily trade-offs, of this are discussed in the section on concurrent development.)

Perseverance, likewise, is also an essential characteristic of engineers as well as artists. For artists, the very process of nurturing a vision from conception to execution is often a matter of perseverance. Obstacles include the financial difficulty of obtaining materials. This may range from the metal sculptor's purchase of raw materials and tools to the musician's purchase of appropriate gear or rental of studio space. Once those resources are present, for the lone artist, there is the challenge of mastering all the techniques and tools necessary to realize a vision, and for the artist working in a group, the dynamics of working with others who also hold artistic visions and sub-visions, and bring different levels of skills to the endeavor is an additional challenge. Added to these are the difficulties brought on by physical limitations of the tools and materials to be used.

All of these obstacles manifest in very similar ways for engineers: Understanding a design problem, developing potential solutions, determining the tools necessary to carry out design strategies, identifying the constraints (physical and social) imposed on the solutions, working in teams with members from different backgrounds, knowledge, and abilities, are all typical challenges for engineers. Engineering teams may sometimes even face similar financial concerns as artists, though likely on a different scale.

Paich's approach to discussing these issues of challenge and mastery is through Nikola Tesla and Leonardo da Vinci whom he presents as problem-solving creators. He argues that creativity, as a condition for problem-solving, is reinforced by certain preconditions: a real-world need, a measurable outcome, and connecting the two, he identifies mental arousal through imagination as the fuel to persevere, to keep ideas alive in the face of ongoing challenges. To be specific, 'imagination' refers to "how a problem is constructed in the mind of the thinker [Paich's model of Tesla] as well as a part of what he or she creatively brings to the encounter with immediate experience [Paich's Da Vinci]"[41]. According to this account, the conception of ideas and the sustained process of problem-solving in the arts, sciences, and engineering share the necessary components of mastery, dexterity, perseverance, and imagination.

A similar list of components is given by Foshay, who approaches problem-solving in the arts from the perspective of elementary pedagogy. His list includes missing information, relationships between concepts, motivation, perseverance, ambiguity, anxiety, procrastination, communication[42], and his framework for problem-solving progresses from the problem domain to the constraints, and then to the required knowledge, clarification of the problem, a strategy for solving the problem, and the analysis of the problem-solving approach[43]. Among problem constraints, the usual elements are identified: time, budget, team members, and materials[44]. Much of the subsequent discussion in this paper focuses on the planning aspect of arts problem-solving in primary education, but includes a discussion of the transfer of these skills to other domains. The types of questioning employed by arts teachers[45] suggests that these arts problem-solving experiences are valuable early-life practice for project planning in secondary and higher education.

Pitri, on the other hand, focuses on "identifying how skills and dispositions related to problem solving are expressed in a child's behavior and artwork"[46] and approaches problem-solving from the point of view of critical thinking. Following a thorough inventory of critical-thinking processes and elements, Pitri stresses the "interpersonal, technical, and conceptual problems"[47] faced by students during art activities, and defines creativity as the ability to "come up with many different, unusual, original, or detailed solutions to problems (Ellermeyer 1993)."[48]

Aside from the obvious connection of these challenges to engineering design and engineering team work, Pitri adds that art activities are intended to "motivate students to think and be engaged in purposeful activity"[49]. A problem in this context is defined as "a situation where a person wants to achieve something but does not know how"[50]. The successful approach tends to be one of "thinking and analysis as well as … play and fantasy (Torrance, 1988),"[51] a combination of "judgment and intuition to select the best solution"[52] and the "commitment necessary to transform their ideas into usable results."[53] All of these attributes are shared among the arts, the sciences, and engineering.

b. Similarities between the Arts and STEM: Problem-Solving and Design under Constraint

Even more direct connections to engineering design exist in the literature on arts problem-solving. Davis' description of the role of design in the arts and the skills required in terms of design thinking and design problem-solving in productive 21st-century adults reads the same as the list of characteristics of next-generation engineers (slightly paraphrased)[54]:

1. Demonstrate the ability to acquire and use knowledge within a variety of contexts rather than amassing specific facts that may eventually become irrelevant.
2. Deal successfully with high degrees of uncertainty in problems, suspending judgment until aspects of the problem have been viewed from multiple perspectives.
3. Invent new paradigms for problem solving that account for increasing levels of complexity and interconnectedness.
4. Master technology and make sense of information to serve larger social goals.
5. Work in teams, drawing on the expertise and creativity of others to solve problems that are too large for a single discipline.

We see that arts education, and arts problem-solving in particular, shares the goals, challenges, and key attributes of engineering design education and engineering problem-solving.

In one last critical way are arts and engineering problem-solving significantly alike. In the Harvard Educational Review, Glass, Meyer, and Rose argue that most content taught in schools is well-structured. They also state that—as we know to be in engineering practice—this is not the case in the arts. The arts are "an ill-structured domain … with unique one-of-a-kind cases where rules and generalizations may not always apply."[55] They fall on the same side of the ill-structured/well-structured divide as engineering design, and on the opposite side from engineering theory. Glass *et al.* also posit that arts education "may be important for developing *cognitive flexibility*—the ability to select relevant strategies…" (a key component to engineering design), and proceed to give examples of cognitive techniques in the arts that could benefit engineers in design teams wrestling with aesthetic, sensory, and economic aspects of a product.

If the arts and engineering share so much in terms of the critical role of problem-solving, we must next ask if there has been any evidence of apparent (not necessarily explicitly measured) skill transfer between the arts and STEM.

4. Evidence for the Benefits of the Arts for the STEM Fields

a. General Evidence

A variety of evidence exists to the effect that the arts, whether through active engagement or otherwise, benefit activities associated with the STEM fields. Some of this evidence, small-scale and correlational without positing a mechanism, has come under strong criticism (as all evidence should), and is considered mostly discredited. It is now difficult to argue that the arts directly improve quantitative thinking merely with short-term exposure.

On the other hand, newer studies examining broader effects and seeking causal connections have been conducted. One such study funded by the National Science Foundation claims statistically significant evidence for a "strong causal relationship between arts-based learning and improved … innovation outcomes in adolescents".[56] The study used externally developed metrics in addition to self-report, and spanned a period of several months. While this is not a career-duration longitudinal study, the pre- and post-observations included a separation from the training sessions by a period of four months, resulting in higher validity than the results of, for example, single-day workshops with pre- and post-tests would have been.

Some of the innovation outcomes discussed in this study are measured improvements among high-school students and early-career professionals: "idea range (13%), problem analysis (50%) and number of solutions generated (37%)" (Ibid.). There is even evidence that "traditional STEM learning" leads to a decrease in these abilities.

However, gains were not observed across the board (in every category) for every group of subjects. The results of this study are encouraging, not absolute. For example, many improvements were higher among high-school students than early-career professionals, and higher for metrics for pure creativity and for problem identification than for metrics for pure problem-solving, but higher again for problem-solving *strategy* and the final innovation output as judged by a panel of experts. The treatment groups also showed significant gains in all aspects of team work, which is an indirect but essential component of engineering problem-solving.[57]

The study investigated the ability to transfer skills from the arts domain (by means of project-based innovation training to STEM problems, used metrics for critical thinking, creative thinking, and problem-solving (CPSP by Basadur, Graen, and Wakabayashi, 1990, which addresses implementation as well as ideation), and compared "arts-based innovation training [with] traditional innovation training"[58].

It is relevant to note that the scope of the project included aspects of implementation. Nonetheless, a reliable conclusion cannot be reached based on one study. There needs to be either independent verification or other evidence to the same effect.

Strong conceptual support comes from the 2004 report of the National Academy of Engineering: "Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance. The creativity requisite for engineering will change only in the sense that the problems to be solved may require synthesis of a broader range of interdisciplinary knowledge and a greater focus on systemic constructs and outcomes."[59] The second sentence refers to an earlier assertion in the same report that engineers should be "educated to understand and appreciate history, philosophy, culture, ***and the arts, along with the creative elements of all these disciplines***."[60]

A research study of a different nature on the positive impact of the arts on innovation in STEM come from a large research team at Michigan State University.

In *Arts Foster Scientific Success*, the team of Root-Bernstein *et al.* report that "Nobel laureates [are] significantly more likely to engage in arts and crafts avocations than Royal Society and National Academy of Sciences (NAS) members, who [are] in turn significantly more likely than Sigma Xi members and the U.S. public" and also that "[s]cientists and their biographers often commented on the utility of their avocations as stimuli for their science. The paper, while not positing a causal connection, is replete with quotations from Nobel laureates who extoll the importance of the arts to scientific work. One of these quotations hints at the main thrust of the present paper, which is that developing a second set of problem-solving skills must aid one's engineering problem-solving skills[61]:

> "Having a large measure of one good quality increases the probability that one will have more than the average of any other good quality. He who can learn better than average through his eyes, tends to learn better than the average through his ears also; …. Artistic ability, as in music, painting, or literary creation, goes with scientific ability …"

This statement from 1911 seems focused on the presence of innate ability, which is an observation—whether true or false—and is neither the topic of the present argument nor one that is in favor due to our present understanding of the interaction of nature and nurture.

The Bernstein *et al.* paper argues against the possibility that the characteristics that accompany coextensive STEM and arts success is not simply a result of general intelligence[62] by showing that intelligence data for the same sets of scientists does not follow the monotonic curve exhibited by arts engagement.

However, it is precisely due to this interaction that if it is true that scientific ability (hence foundational engineering ability) and artistic ability necessarily coexist, then it is reasonable to expect that developing practical "making" skills (which include problem-solving) in one area is likely to improve such skills in the other area.

Such a claim could be considered vacuous if the correlation between science and art engagement were weak or if there were no other evidence to that effect. Fortunately, not only is there further evidence, as discussed throughout this paper, but the correlation is strong both quantitatively and qualitatively. For the qualitative aspect, note the observation that carrying out an artistic avocation "more intensively" (in contrast with the mere presence of such engagement) correlates with scientific success[63]. What is more, the correlation is monotonic: Scientific success increases with the increased level of prestige going from Sigma Xi membership to NAS or Royal Society membership to the Nobel Prize.

The study is quite extensive, including "all Nobel laureates between 1901 and 2005" and records regarding members of the Royal Society and the NAS of scientists for 73- and 128-year contiguous periods, respectively, although the data for Sigma Xi members and the U.S. public come from single-shot surveys[64]. Effort was made to make up for the difference in information available for Nobel laureates and all other scientists[65]. The characterization of a scientist as having had significant arts engagement was not based on vague statements of "having an artistic personality" or an interest in the arts, but from a combination of the person's artistic products, their biographies, and records of their formal arts education[66]. Further caveats about the availability of data and the existence of confounding factors are given in the paper[67]. Taking these into account, the summary finding is that regular ("typical") scientists and the U.S. public average the same amount of active arts engagement, and that scientists honored with a membership in NAS or the Royal Society are twice, and Nobel laureates three times as likely, with $p < 0.0001$[68] to engage actively in an art form. Assurances are made in the paper, using data, that these scientist─artists are or were accomplished practitioners of their art forms, "not mere dilettantes"[69].

One prominent scientific example not explicitly discussed in Root-Bernstein *et al.*'s summary is Walther Bothe, Nobel Prize winner and co-pioneer of the use of "coincidence methods"[70] according to Lawrence Krauss' 2017 history of physics, who started out as a "young student of mathematics, physics, chemistry, and music at the University of Berlin[71], and made the first known experimental observation of neutrons (well before they were thought to exist)[72].

A similar claim to Root-Bernstein *et al.*'s, but with the likelihoods of Nobel laureates broken up by artistic area was reported in *Scientific American*, according to the online journal *The Science Teacher*. The preferences shift for Nobel laureates who are "17 times likelier than the average scientist to be a painter, 12 times more likely to be a poet, and 4 times more likely to be a musician (Pomeroy 2012)[73].

The discussion section delves into the nature–nurture question, arguing that the data suggests "functional connections between scientific talent and arts, crafts, and communications talents so that … developing one fosters the other(s)" and that these skills "interact positively"[74].

For statistical evidence to the effect that arts education benefits science, engineering, and general problem-solving performance overall, we can point to the work of Chishti and Jehangir[75], for experimental studies on the benefit of primary-school arts education on divergent thinking, the work of Sowden, Clements, Redlich, and Lewis[76], and for additional anecdotal experiences on the positive influence of transdisciplinary collaboration on higher-order thinking skills, to the work of Wagner, Baum, and Newbill[77].

b. Specific Benefits of the Arts for STEM

As for specific gains experienced by arts-educated individuals, substantive engagement in the arts helps one develop STEM skills such as "hand[–]eye coordination; knowledge of tools and processes; better visual imagination; improved ability to communicate using words, images, and models; the stage presence of the practiced performer; and a refined scientific aesthetic sensibility"[78]. The importance of some of these skills to science, but also to engineering practice and engineering education, is evident in the following quotation.

> "I think that much of my talent and enjoyment at improvising solutions to experimental problems goes back to those homebuilt projects. . . . Carrying out these individual projects also developed in me a good sense of self-reliance and a sense when a piece of improvised apparatus was likely (or unlikely) to be adequate. This sense is one that I often see missing in students whose education has been confined to formal instruction."[79]

It is not only that these skills, and the artistic exploratory bent that accompanies them, are essential to experimental problem-solving according to a few scientists. The above list of skills also constitutes a significant subset of the student-learning outcomes (ideal results) articulated by ABET for engineering[80]:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

"Hand–eye coordination" and the "knowledge of tools and processes"[81] figure into outcome (b), and the latter into outcome (k) as well. As argued throughout this paper, "better visual imagination"[82] can contribute to outcome (e). Both "improved ability to communicate using words, images, and models" and "the stage presence of the practiced performer" are components of outcome (g).

The last of Root-Bernstein's skills, "a refined scientific aesthetic sensibility," requires more thought, and is elaborated on in the following section.

c. Cases in Art-Based Success in Engineering and Technology

It was necessary to start out by positing the role that divergent thinking, creativity, experimentation, and openness to new ideas as fostered by the arts could, or even must, contribute to engineering problem-solving, but without a few concrete examples, it would be fair for the reader to remain skeptical. The cases that follow are specific situations where the arts (and other stimuli) have contributed directly to the solution of technological problems.

The role played by mathematical modeling informed by visual art and the observation of natural phenomena in the development of a practical technique that was utilized in an oil-spill clean-up was presented at the Bridges conference of 2012. In this case, a chemist's intuition about molecular forms was sparked by the combination of mathematical visual art and the experience of raindrops on water, leading to the development of a molecular form that helped the collection of oil molecules in sea water.[83]

In more general terms of creativity than the impact of a particular form of art, one of the co-inventors of the successful Ebola vaccines ZMapp and VSV-EBOV has credited this success to having been at environments that allowed creative exploration by scientists (as well as international collaboration), and emphasized that letting the creativity of scientists roam free is the key to development that is both successful and fast.

A very important example that was almost lost to history is the discovery of spread-spectrum communications, one of the fundamental techniques for cell-phone communications, during World War II by a musician–actress (the originator of the concept) and a composer–inventor–munitions-inspector (the developer of the implementation).[84]

While the full story is rather involved, both inventors played the piano and it was this mechanical interface for the selection of frequencies (musical notes) that inspired in eminent actress Hedy Lamarr the idea for frequency-hopping for a torpedo-control system that could not be jammed. Likewise, it was her friend the renowned composer George Antheil's experience in mechanically synchronizing player-pianos for modern compositions that led to the practical implementation of Lamarr's idea. The following passage from a recent book on Lamarr and her invention, edited due to its extremely long list of technologies, places in today's context the downstream domino effect of a movie star and a composer, both of whom were knowledgeable about weapons and mechanics, sitting at a piano, thinking outside the box. According to its author Rhodes, the spread-spectrum concept, directly based on Lamarr's frequency-hopping:

> "… enabled the development of Wi-Fi, Bluetooth, … and GPS. Wireless local[-]area networks (wLANs) use spread spectrum, as do wireless cash registers, bar-code readers, restaurant menu pads, and home control systems. So does Qualcomm's Omni-TRACS mobile information system for commercial trucking fleets. So do unmanned aerial vehicles (UAVs), electronic automotive subsystems, aerial and maritime mobile broadband, wireless access points, digital watermarking, and much more.
>
> A study done for Microsoft in 2009 estimated the minimum economic value of spread-spectrum Wi-Fi in homes and hospitals and RFID tags in clothing[-]retail outlets in the U.S. as $16–$37 billion per year. These uses, the study notes, 'only account for 15% of the total projected market for unlicensed [spectrum] chipsets in 2014, and therefore significantly underestimates the total value being generated in unlicensed usage over this time period.' A market of which 15% is $25 billion would be a $166 billion market.[85]

In analyzing how Lamarr and Antheil moved from disconnected knowledge of weapons, radios, and pianos to the emergent notions of frequency hopping and synchronization, one of the consultant's to the author of the Hedy Lamarr story, an inventor and engineer, explains what it takes to connect unrelated concepts for invention: "'the inventive process follows a cascade of ideas and thoughts interconnected from previous concepts that for the most part lie separate, unconnected and unrelated. It takes a clear state of mind, which is usually someone thinking `outside the box,` to suddenly or serendipitously see the connection between the unrelated concepts and put it all together to create something new.' In that regard, the process of invention is no different from the creative process in other fields. Scientific discovery proceeds the same way. So do painting and sculpture. So does creative writing."[86]

5. In Conclusion, STEM and the Arts, from the Point of View of Problem-Solving and Design-under-Constraint

The number-one action recommendation from the joint report of the NSF and the NEA is that "[l]ong-term funding initiatives are needed to maintain U.S. competitiveness in the international Art + Science + Technology research arena."[87]

As discussed previously, engineering design involves such elements as problem-solving, decision-making, team work, concurrent development, analysis, synthesis, and creativity. It makes extensive use of mathematics and the sciences as its very basis, and it ultimately deals with economic and social factors. The designer often creates a product or solution that is new, novel, or innovative. (And sometimes the solution is brilliant in its simplicity.)

Less well known are the roles of problem-solving, decision-making, team work, concurrent development, analysis, synthesis, and even the sciences and mathematics in the creative processes of the arts. The artist, like the engineer endeavors to create a new, novel, or even innovative product. The value of the artistic product is judged by the market in terms of its cost, aesthetics, social impact, and sometimes even safety, just like the products and solutions of engineering work. (And a few are also brilliant in their simplicity.)

Furthermore, just as the engineer has to construct, test, and evaluate a design, artists also construct their works (whether physically out of raw material, or conceptually as organizations of sound in time), test them via exhibits or performances, and evaluate their own and others' works.

Just as the social impact of engineering designs is a substantial enough concern to find its way into the criteria for accreditation, the social impact of various art forms have also come under scrutiny, especially as they incorporated modern technology into their creative processes.

Naturally, there also are aspects of engineering design that may find no parallels in the arts: the critical importance of reliability, for example, or the need for detailed documentation. The objective is not to argue that all elements of engineering design are found in, or have parallels in, the artistic process, but to demonstrate that perhaps many more elements of engineering design than are typically thought of can be found in varying degrees of close relationships to the problem-solving processes of the arts.

If engineering students are exposed in significant ways to the problem-solving, decision-making, team work, concurrent development, analysis, synthesis, and creativity aspects of the artistic process, they would find the opportunity to transfer these skills, and apply them to their engineering work—a higher level of thinking outside the box than we typically have in mind.

Moreover, most art forms, even the folkloric ones, have strict conventions that are painstakingly learned and are executed with great precision. An expert artist is one who knows and can execute all conventions thoroughly accurately, but *must* also balance this with innovation. Likewise, engineering education balances the foundational role of theory—of the fundamental and engineering sciences, and of mathematics—with the intuitive creativity of the budding engineer who cultivates a gut feel for what the problem needs.

The arts, then, as a whole, are based on design under constraint, which in turn relies on problem-solving ability involving all of the skills and challenges discussed in the present paper.

6. Position Statement (Conjecture)

Engineering students who experience the arts actively and significantly can benefit from the cognitive habits of one pursuit while developing in the other, and vice versa. This is because art-making, when practiced by experienced individuals—not necessarily experts, but those with some substantive engagement that progresses from lower or nonexistent skill levels to medium skill levels—is a practice that integrates problem-solving as an essential component, similar in nature to problem-solving in engineering.

7. Problem Statement (Hypothesis)

Practicing substantial problem-solving in an additional field that involves design constraints, trade-offs, costs, and "making" as central components, confers an aggregate benefit on the problem-solving skills of engineering undergraduates as compared to such skills in students who practice problem-solving in one field alone.

8. Proposed Work: Research Design

a. Formative Arts Training for Engineering Students

We propose a parallel "mini curriculum" in one form of art (to be selected by each student and their arts advisor based on the students experience or interests), and an accompanying scholarship, that will allow the student to experience substantive and progressive involvement in the chosen art form (not a survey of art, not a course on appreciation, but active "making" in which the student is expected to progress) such that problem-solving as defined above, <u>*the identification of resources, strategies, constraints, risks, and trade-offs for meeting an open-ended, multi-solution spec in the presence of ambiguity and variability, through the process of design under constraint*</u>, can be experienced by the student prior to their fourth-year engineering design project.

Each such mini curriculum, as allowed by institutional resources, will be designed in conjunction with arts faculty in each pertinent arts department or field.

b. Assessment of Project Creativity and Problem-Solving

Assessment instruments will be developed by the PI, the author of the present paper, based on approximately a decade and a half of assessment (specifically rubric design, rubric norming, rubric implementation, and survey design) experience in the arts, in critical thinking, and in engineering.

Since the population of students who may choose to take this route for their engineering education is likely to be small, especially at a small university, incoming students' past experiences with the arts also need to be taken into account. For this purpose, the department of Electrical and Computer Engineering has drawn up the following extensive list of art forms.

- poetry
- creative writing
- painting
- drawing
- sculpture
- printmaking
- ceramics
- photography
- dance performance
- choreography
- dance direction
- film direction
- film-making
- music performance
- music composition
- music production
- performance art
- theater production
- theater performance (acting)
- set design
- architecture
- industrial design, and
- digital/mathematical art.

i. Piloting Assessment for Inter-rater Reliability

The present author has several years of experience developing painting and drawing rubrics with art faculty, as well as substantial experience designing rubrics for engineering labs and engineering project reports. Therefore, direct assessment of problem-solving evidence using rubrics is planned as the central piece of the data-gathering process for evaluating problem-solving performance.

During the first year—the 2017–'18 academic year—rather than collect data for analysis, the assessment instruments (primarily rubrics for design projects) will be used to test for inter-rater reliability among the department's dozen or so faculty who regularly evaluate all design-team projects. Based on the findings of this pilot run, rubric-norming sessions may be run, if deemed necessary.

Furthermore, since the incoming student cohort, with the exception of transfer students, will neither be working on their fourth-year design projects nor will have spent sufficient time in their mini arts curricula, the second year will be used to pilot all aspects of the design: the mini curricula, the data collection, and further tuning of assessment instruments.

ii. Assessment Instruments

In a series of articles chronicling their research into the characteristics of engineering innovativeness (and the related topic of ideation in engineering design), the team of scholars Jablokow, Yılmaz, Samuel, Purzer, Menold, Parker, and others conclude that there is no one validated comprehensive assessment instrument for engineering innovativeness. However, their studies of both innovativeness itself and of the instruments available for assessing the related qualities of innovativeness, creativity, entrepreneurship, and design problem-solving[1] provide us both with further valuable information about pertinent connections between the arts and engineering problem-solving and about the usefulness of various instruments for the more specific assessment task of interest in the present study.

This group of researchers (in a variety of papers cited individually below) have analyzed frameworks of innovation, instruments of its assessment, and other aspects of ICEDPS. In their study of prior research, they have reviewed more frameworks than are relevant to the present study, but four are summarized here because of their role in the choice of innovativeness assessment instruments that have the potential to be useful for the present purpose.

One of these is the Hunter et al. study on an innovative workforce[88–95] In this framework, innovativeness is modeled in terms of knowledge, in terms of skills, and in terms of abilities. Knowledge is said to come in a domain-specific and a broad type. Skills are also either domain-specific or creative. Abilities include several that are especially relevant to linking artistic creativity to engineering creativity: divergent thinking, associational ability, and analogical ability (Ibid.). It is these three abilities in particular that, from the cognitive and assessment points of view, support our argument throughout this paper that the arts and engineering engage the same creative and innovative problem-solving faculties.

A second framework is due to Schindel et al. (based on Dyer et al.[2]) (Ibid.), and identifies three dimensions of innovativeness: discipline competencies, systems competencies, and discovery skills or competencies (Ibid.). The first two are clearly and typically recognized as critical to engineering success (such as a stakeholder perspectives, technical knowledge, and feasibility (Ibid.), but they also possess important connections (such as critical thinking) to the humanities as well as the sciences. In the discovery category, the competencies "associating, ... observing, [and] experimenting" are ones that are strongly associated with the arts. Their prominence in frameworks of engineering innovativeness provides additional credence to the conjecture that substantial engagement in an art form can enhance engineering problem-solving skills.

Another of the discovery competencies in the Schindel/Dyer framework is "networking" (Ibid.). This is a relative weakness in engineering education and in the typical engineer's skill set, and less so in the typical artist's skill set. The arts are a social lubricant, and enhancing engineers'

[1] Let's call this set of skills or attributes "ICEDPS" for ease of reference below.
[2] The source study by Dyer et al. was "validated and tested on 6000 business professionals, approximately 40% of whom were engineers." (Ibid.)

networking abilities (for problem-solving purposes as well as research or job-search purposes) is something arts engagement would also be poised to contribute to considerably, as a side benefit.

The third framework is due to Fisher et al., and includes the highly arts-affiliated attributes "comfort with multiple perspectives, curiosity, confidence, [and] informed risk-taking"[88]. This pilot study has also demonstrated, based on "ten innovation experts"[88] that characteristics that impede innovation "include lack of confidence, risk aversion, and being overly critical of self and others.[88]" Here we see yet another way training in the arts can help overcome emblematic engineering shortcomings.

The authors of the study on innovativeness-assessment instruments focus last on the framework of Ferguson as being the best prior research for purposes of engineering innovativeness due to its validation by "expert engineering innovators [imbuing the study with] practical relevance." (Ibid.) The 20 characteristics of engineering innovators discussed through which assessment instruments are evaluated come from the Ferguson study of 45 "expert engineering innovators.[95]"

These 20 characteristics are further refined and explained in the Menold et al. article, and based on this analysis, a subset of the 20 characteristics and a subset of the evaluated assessment instruments are taken into account for the slightly narrower scope of the present paper.

Menold et al. present a cognitive (cognitive-science-based) framework for breaking up the capabilities of innovative engineers into three categories called *cognitive affect*, *cognitive style* (later called *cognitive effect*[96], and *cognitive level* (later called *cognitive resource*)[96].

Cognitive affect is the designer's (problem-solver's) set of attitudes and beliefs[97]. It is most prevalent prior to the problem-solving stage because it deals with the selection and prioritization of problems. However, in team problem-solving (team design), the selection and prioritization of (sub)problems is a critical aspect of engineering problem-solving, and is thus relevant to our concerns here.

Cognitive *effect*[88], or cognitive style[97] is also called "problem-solving style" [88]; thus it is centrally relevant to the problem at hand.

Cognitive resource (or cognitive level) includes both existing knowledge[96] and "potential level" which is one's "intelligence, aptitude, and talent.[88]" While all of these attributes are relevant to problem-solving, the present concern is with those attributes that can be learned or enhanced, so the focus will be on those closer to the 'learned' end of the innate–learned continuum.

Based on these cognitive categories, along with their commonalities and the interactions these attributes can have in individuals, Menold et al. classify the 20 characteristics of innovative problem-solvers into primarily and secondarily innate and learned attributes, and then apply the resulting breakdowns to the evaluation of a variety of assessment instruments in three categories: entrepreneurship, information processing, and self-efficacy.

In the present paper, this evaluation is further refined to focus on instruments that are pertinent to the ICEDPS aspects of the engineering-innovativeness domain.

Out of the 20 Ferguson characteristics, we focus on the following as particularly pertinent to engagement in the arts: ‘alternatives seeker’, ‘associative thinker’, ‘challenger’, ‘collaborator’, ‘communicator’, ‘creative’, ‘curious’, ‘passionate’, ‘persistent’, ‘risk-taker’, ‘self-reliant’, and ‘user-empathetic’.

In addition, we mark ‘challenger’, ‘collaborator’, ‘creative’, ‘curious’ and (missing from the previous list) ‘implementer’ as typical of both engineers and artists. (These choices were made by the present author, based on personal experiences in both the arts and engineering, and may need to be externally validated before this study proceeds to assessment design.)

An important distinction Menold et al. make is as to whether these attributes are (primarily or otherwise) innate or learned. It is essential to the present conjecture that *learned attributes* are assessed. Hence, the subset of primarily or secondarily learned attributes is: ‘alternatives seeker’, (secondarily learned), ‘associative thinker’ (secondarily learned), ‘collaborator’, ‘communicator’, ‘creative’, ‘implementer’, and ‘user-empathetic’ (secondarily learned).

As a result, the present study focuses on those favorably reviewed instruments that were found to be particularly relevant to the final subset of characteristics. The outstanding candidates among the instruments are the California Critical Thinking Disposition Inventory, the Kirton Adaptation–Innovation Inventory, and Kolbe's A (Conative) Index[88].

Although Menold et al. conclude that the instruments studied are ineffective for assessing the complete set of 20 attributes of engineering innovators, a combination of these instruments and custom-developed instruments at our institution are expected to suffice for assessing problem-solving in (junior or senior) engineering design in our upcoming APS4EPS sub-curriculum.

Further assessment instruments for this research and its implementation are to be developed in collaboration with the departmental engineering faculty, and where necessary, with the arts faculty.

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