Enabling creative collaboration for all levels of learning

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A potential path for enabling greater creativity and collaboration is through increased arts and science, technology, engineering, and mathematics (STEM) integration in education and research. This approach has been a growing discussion in US national forums and is the foundation of the science, technology, engineering, and mathematics plus arts and design (STEAM) education movement. Developing authentic artistic integrations with STEM fields (or vice versa) is challenging, particularly in higher education, where traditional disciplinary structures and incentives can impede the creation of integrated programs. Measuring and assessing the outcomes of such integration efforts can be even more challenging, since traditional metrics do not necessarily capture new opportunities created for students and faculty, and the greatest impact may occur over a long period (a career). At Drexel University, we created the Expressive & Creative Interaction Technologies (ExCITe) Center as a standalone institute to pursue and enable such transdisciplinary arts–STEM collaborations, particularly with external arts and education partners. In this perspectives paper, we highlight a range of projects and outcomes resulting from such external collaborations, including graduate research with professional artists, undergraduate student work experiences, and STEAM-based education programs for kindergarten through 12th-grade (K-12) students. While each project has its own specific objectives and outcomes, we believe that they collectively demonstrate this integrated transdisciplinary approach to be impactful and potentially transformative for all levels of learning.

interdisciplinary research | creative collaboration | arts technology | STEAM education | music

Many leaders in education, government, and industry have expressed a desire for 21st century graduates to be more creative and collaborative (1–3). The decades-long emphasis on science, technology, engineering, and mathematics (STEM) education has been pursued in the name of greater innovation in academia and industry. However, programs in STEM fields tend to emphasize convergent thinking and disciplinary depth and do not generally incorporate training for creativity and collaboration (4–6). Some emerging fields and research areas build on the foundations of STEM but also incorporate a strong element of arts and design, integrating multiple disciplines to advance knowledge. This is commonly referred to as science, technology, engineering, and mathematics plus arts and design (STEAM), and it has been a growing topic of conversation, particularly among education researchers and practitioners.

Historically, Leonardo da Vinci, Benjamin Franklin, and Alexander Graham Bell are prime examples of the potential advances from integrating artistic and scientific pursuits. There is a small but growing body of evidence that arts integration can positively impact STEM research. There is a significant correlation between arts participation and the highest levels of scientific achievement. Nobel prize winners are 25 times more likely than the average scientist to sing, dance, or act. A disproportionate percentage of National Academies members in the United States and Royal Society members in the United Kingdom participate in the creative and performing arts (7). Dr. Donald Ingber has spoken of his discovery of tensegrity in cellular structures, which was inspired from a sculpture class studying the designs of Buckminster Fuller and Kenneth Snelson that he took as an undergraduate student (8).

Thus, it is not surprising that several recent initiatives of the National Academies of Science, Engineering, and Medicine have focused on the creative connections between the STEM fields and the arts for advancing discovery, innovation, and learning. These include the Keck Futures Initiatives [multidisciplinary conferences, particularly the 2015 meeting focusing on art–science collaborations (9)] as well as the 2018 consensus report *The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree* (10).

Furthermore, it is becoming clear that industry is seeking different skills than those emphasized in traditional university training. More and more, corporate leaders are calling for creativity as the most desirable trait in potential employees (2). IBM has invested heavily in training so-called "T-shaped" workers, with depth of skill in one area but also breadth to interface and collaborate with others. This approach tends to increase the diversity within teams (in both approach and demographics) and fosters creativity in problem solving. The enormous success of Apple, Inc. has been attributed, in part, to their corporate culture encouraging even those employees who are experts in highly specific technology domains (computer scientists and engineers) to value design and incorporate design principles into their processes (11).

Despite the potentially transformative gains of arts–STEM integration, it has been challenging to implement such approaches in higher education due to the traditional disciplinary structure of institutions. Institutions have pursued a variety of interdisciplinary programs and initiatives to address these evolving needs and opportunities. Some of these efforts, such as the MIT Media Laboratory (https://www.media.mit.edu) and Arizona State's School of Arts, Media, & Engineering (https://artsmediaengineering.asu.edu), are at research universities, while others have emerged from premiere arts and

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design institutions, such as Rhode Island School of Design (https://stemtosteam.org) and OCAD University (12). These and a number of similarly spirited programs have greatly informed our efforts.

In this paper, we detail the overall approach and emerging outcomes from the Expressive & Creative Interaction Technologies (ExCITe) Center at Drexel University, which offers a distinctive approach for arts–STEM integration spanning research and education activities emphasizing external collaboration and engagement. These programs range from middle school outreach to postgraduate collaboration with professional performing artists. Because of the diversity of projects and activities, there is no single way to capture and assess all of the processes and outputs. Here, we take a multidimensional approach, collecting information from interviews with external collaborators, internal student surveys and reflections, and assessments administered in kindergarten through 12th-grade (K-12) programs. Although many of these outcomes are still emerging, we believe that these analyses help to develop an overall picture of the effectiveness and positive impact of STEAM-based collaboration across a broad range of learning levels.

About the ExCITe Center of Drexel University

We established the ExCITe Center in 2013 as a research institute to serve as a hub for transdisciplinary[*] collaboration. The center does not belong to any single academic unit but reports to the Office of Research, bringing together faculty and students from across the university for the following collaborative efforts.

- Research: ExCITe is an incubator for faculty-led transdisciplinary research in emerging areas, such as smart "functional" fabrics, videogame design, music and entertainment technologies, and humanoid robotics.
- Education: Faculty and students develop arts-integrated approaches to teaching and learning through novel STEAM programs.
- Civic engagement: All ExCITe efforts emphasize public engagement, often in partnership with the community and civic organizations benefiting the Philadelphia region.

The center houses three faculty research laboratories (the Center for Functional Fabrics, the Entrepreneurial Game Studio, and the Music and Entertainment Technology Laboratory) as well as a common collaboration space for affiliated faculty and students. Affiliated faculty members span Drexel's Colleges of Engineering, Media Arts and Design, Computing and Informatics, Education, and Arts and Sciences. The center also hosts numerous education and public outreach programs. Some highlights from the brief history of the center are as follows.

- Groundbreaking work in smart fabrics by Prof. Geneviève Dion and a leading role in establishing the Advanced Functional Fabrics of America, a US National Network of Manufacturing Innovation Institute (go.affoa.org).
- A Guinness World Record for the largest video game display for a city-wide playable version of Tetris on a Philadelphia 30-story skyscraper (Prof. Frank Lee; https://bits.blogs.nytimes.com/2014/04/06/making-a-game-larger-than-life/).
- The magnetic resonator piano (MRP) (13), a unique augmented musical instrument developed by (then) postdoctoral fellow Andrew McPherson, which has been featured in performances in the United States and Europe. The MRP includes breakthroughs in both real-time electromagnetic control and novel keyboard sensors that provide a performer-friendly interface.

For the remainder of this paper, we focus specifically on the center's arts-integrated, collaborative STEAM projects and activities, viewing outcomes from artistic, research, and learning perspectives. Many examples originate from the Music & Entertainment Technologies Laboratory (MET-lab), which has engaged in numerous arts–technology collaborative projects with renowned professional artists and arts and education organizations.

Extended Artistic Collaborations

MET-lab has worked with a variety of external collaborators on large-scale arts–technology projects. The laboratory partnered with the Philadelphia Orchestra to develop LiveNote, a system based around a smartphone app to provide audiences with additional information (musical and historical context) about an orchestral piece as it is performed (14). A team of graduate and undergraduate students also developed real-time acoustic visualizations for live musical performances, which were presented in multiple events with Grammy-nominated jazz musicians Marc Cary and Will Calhoun (drexel.edu/excite/news-events/events/2013-2016-events/Science%20of%20Jazz/). In 2016, undergraduate students from the center partnered with Parsons Dance of New York City to premiere a new work featuring human dancers with drones simultaneously on stage. Several of these projects have jointly advanced both art and fields such as machine listening and human–machine interaction, advancing artificial intelligence systems that recognize performer expression and perceived emotions in music (15).

Most recently, ExCITe researchers engaged in two separate extended (1 y or longer) collaborative projects with external artistic collaborators that were presented in 2017, which we describe in greater detail below. We then present interviews with the external collaborators to reflect on the process and assess the outcomes of these projects.

Sophia's Forest. Starting in the 2015–2016 academic year, we began collaborating with renowned composer Lembit Beecher (composer in residence with the St. Paul Chamber Orchestra and former composer in residence with Opera Philadelphia, which initiated this collaboration) to create novel musical instruments for a chamber opera through a grant from the Pew Center for Arts and Heritage (Fig. 1). The objective of this collaboration was to create robotic "sound sculptures"—acoustic instruments that also composed the scenery of the opera, providing a spatial ambience to the work. Two types of instruments were developed: a vertically oriented glass armonica to produce a variety of sustained tones and a spinning wheel "drum" to generate percussive sounds. Designer Simon Kim and his students from the University of Pennsylvania also created enclosures for the instruments to further incorporate them into the scenery.

The design of these instruments was largely driven by the vision of composer Beecher, who had already conceived of the general theme of the opera with preliminary ideas regarding the instruments and sounds. However, throughout the process, the composer adjusted his pieces based on the sounds produced by the sculptures, while engineers adjusted the design and output of the sculptures to match the composer's idea of the piece.

Sophia's Forest premiered at Drexel University's Black Box Theater in the late summer of 2017 to an audience of several hundred, receiving positive reviews (best of 2017 in concert halls: www.philly.com/philly/columnists/david_patrick_stearns/david-patrick-stearns-best-of-2017-in-concert-halls-and-in-mongolia-20171227.html). The performance integrated nine mechatronic

[*]Although the terms interdisciplinary, multidisciplinary, or transdisciplinary are sometimes used interchangeably when referring to collaborative research involving multiple fields, we use transdisciplinary to describe the proposed program (distinct from interdisciplinary and multidisciplinary research). According to the Collaborative Institutional Training Initiative Responsible Code of Research used by many Institutions for research training: "Transdisciplinary research refers to an even more collaborative form of work, in which researchers approach a common problem from an integrated conceptual framework, identifying the discipline-based methods and approaches that they can take together and redefining both the problem and its solution accordingly."

Fig. 1. Scene from *Sophia's Forest* (September 2017) featuring soprano Keira Duffy and the Aizuri String Quartet. Visible at the edges of the stage are several instances of the mechatronic percussion wheel and vertical glass armonica instruments developed specifically for the work.

instruments—four glass armonicas and five spinning percussive wheels—controlled by the composer through a musical instrument digital interface controller over a wireless network connection. The award-winning Aizuri String Quartet (string quartet in residence at the Curtis Institute of Music, 2016–2017: https://www.aizuriquartet.com) completed the instrumentation, and the lead role was sung by renowned soprano Keira Duffy (kieraduffysoprano.com/about/).

Drumhenge: An Artist-in-Residence Project In 2016–2017, the ExCITe Center engaged in a unique artist residency project supported by a grant from the Knight Foundation to pursue the creation of new technology for live music performance (Fig. 2). In contrast to prior projects pursued in collaboration with professional musicians, this was the first initiated by ExCITe to start with a blank slate without a specific technology concept or objective. In this case, the project was designed to include the artist in residence as an equal voice in every phase of development from initial ideation through development to performance. This full-year residency was intended to enable a more participatory and iterative development process than engineering researchers might undertake working in isolation.

From a range of competitive applicants for the musical artist residency, in early 2016, we selected Philadelphia-based composer, performer, music producer, and filmmaker Peter English to work in close collaboration with MET-lab electrical engineering PhD candidate J.G. (also a multiinstrumentalist). The codesign process with the artist served to better align technical advances with creative possibilities and affordances.

Although conversant with the technology of modern music and video production, English relied on feedback from J.G. regarding what was technically feasible and realistic. In that sense, the technical approach often illuminated possible artistic paths, with artist and engineer jointly selecting the particular avenue to travel. The compositional process progressed in step with the technical development, with each iteration testing and stretching abilities of both artist and engineer. On the codesign process, English notes:

> It's hard to even figure when the exact idea started, but there [were] creative ideas around and then Jeff pitched me a piece of technology and then I would look at it and go, "Oh my God, can it do this?"...And it just kept going...It was a real extension of both of our interests and both of our abilities.

Early on, multiple concepts were prototyped and discarded before the team settled on the design for their new instrument. The residency culminated in the summer of 2017 with a live performance at Drexel. Billed as *Drumhenge: A New Musical Instrument*, the performance featured a network of 16 acoustic drums ("Drumhenge"), each augmented with an electromagnetic actuator capable of driving the resonant membrane (the bottom "head"). Controlled by an onboard microcontroller, each drum becomes an acoustic synthesizer capable of producing a wide range of timbres (as well as lighting effects via embedded LEDs). The drums are connected via Wi-Fi, forming a networked ensemble instrument (16) where signals can propagate from one drum to another, an example of the "Internet of musical things" (17). In the performance, a four-piece band encircled by the network performed several original compositions and cover songs arranged to highlight specific capabilities of the new instrument.

One concern with research involving music performance is the difference between laboratory data collection and a live concert with an audience. A secondary goal of this project was to develop a system able to capture and extend a musician's interaction with the instrument in an authentic performance setting. Similar to the MRP, the initial interface is intuitive to a seasoned performer (press a key or hit a drum) and can be used to capture interaction with high resolution (precisely how each drum is struck). While the potential of extended modes for expression (via proximity sensors and external computer control) may appeal to professional performers, such in situ performance data collection also requires close collaboration between artists and technologists. The design of Drumhenge is detailed in refs. 18 and 19, and videos of the performance are available online (www.drumhenge.com).

Artist Reflections. In early 2018, we interviewed both of the external artistic collaborators: Peter English and Lembit Beecher (conducted by postdoctoral researcher K.E., who had no prior affiliation with either project or interview subject). Questions focused on comparing and contrasting their experience working with the ExCITe Center vs. their normal collaborative channels and creative processes. Although their stylistic backgrounds varied considerably—from English's independent music leanings to Beecher's formal background in classical and operatic composition—the interviews touched on similar themes.

Both noted that the experience provided a great learning opportunity, challenging them technically and creatively in new ways but finding strong parallels with their existing creative processes. English spoke to the process of asking the same types of fundamental questions that he normally does in his work but applied to a new domain with the assistance of experts.

Fig. 2. A view of the *Drumhenge: A New Musical Instrument* performance (June 2017) featuring composer and codesigner Peter English (keyboard and vocals), codesigner J.G. (Drumhenge control), Max Cudworth (saxophone), Aaron Liao (bass), and Chris Powell (drums). The individual drums of the instrument surround the performers, lit mostly in blue (in addition to acoustic sound synthesis, each drum provides visual feedback through full-color LEDs).

Working with the ExCITe Center totally pushed me into new territory, but it did also show me that from an experience design standpoint and a product management standpoint, the questions are very similar...What does the audience need to be feeling? What do we need to make sure they know or don't know? What do we need to make sure they know is allowed or not allowed? These are questions that are hugely technical but also very creative, and so working at ExCITe I had to apply these two very, very new areas for me.

Both felt that working with the ExCITe Center allowed their work to reach new audiences, with this aspect being a strong motivator for pursuing future collaborative work of this nature. Beecher noted:

> I'm definitely very excited about this sort of work, partly because of the sonic and dramatic potential, but also because of the potential for providing an access point or an interest for people...There's some immediate interest in this sort of unusual production of sound and a visual interest in these sculptures...I think that might be something that would intrigue people who have little interest in the words "opera" or "new music" or "classical music."

English attributed a significant portion of his artist residency's capstone performance audience to ExCITe's network and the success of the event to assistance and domain knowledge from ExCITe students and staff.

> I feel like it gave me the opportunity or the experience to be able to reach out to new audiences because of the work I was able to do and the reputation that the ExCITe Center and that Drexel have...the fact that I can say, "I collaborated with engineers at Drexel to build a new musical instrument using cutting edge technology," that sentence works. People respond to that sentence.

Asked to reflect on the quality of their work with ExCITe, both artists were pleased with the result but expressed caveats that they or other artists should take note of before undertaking such a collaborative effort involving technology development. Beecher notes:

> I think it made me convinced of the possibilities and the expressive potential. The cautionary note that I feel is that the complications of the technology often are greater than one would expect and achieving the reliability that one would like is always difficult.

Similarly, English spoke to limitations of time constraints, which can be exacerbated by uncertainties introduced by a technology development cycle, noting that "I feel like sometimes, in the argument of research vs. art, that the art won because, in part, the grant wanted an end product." He further emphasized the ongoing nature of this work outside the span of the residency.

> There's a lot of conceptual questions, a lot of experiential questions, a lot of interaction questions that we just never got to. I don't look at those as failings, especially because they've been opened to leveraging that technology for other things...There's always things you want to do better and there's always more opportunity that you want, but overwhelmingly I would rate it artistically as successful.

Regarding the sustainability of this type of work, whether undertaken independently or mediated by a research institution, both artists brought up the difficulty of obtaining adequate funding and support. English noted that, having gone above and beyond his estimated time commitment, he would pursue future opportunities only after careful consideration of impact on income and opportunity costs.

> The amount of money that was provided, the tradeoff of what I was able to accomplish and what that does for my body of work and my reputation I would say generally was worth it, but over time it's not a sustainable model. I couldn't keep doing things at this scale at this time commitment and so that's tricky.

Similarly, Beecher emphasizes the importance of the long-term aspect of collaborative work, which is not always supported long term.

> I think like any art form, working with technology, combining opera or combining music and technology, will only reach its potential when the creators, most of the artists, the engineers, everyone involved, is able to iterate. And I think that's somewhat at odds with the business model of a lot of performing art organizations that are finding that the subscription model—the idea that people buy a subscription for the season and go to whatever they want, go to every show—that's sort of starting to die, and people want to go to special experiences.

When asked about the rarity of opportunities for collaborative work with technologists or research institutions, both artists suggested that there is a significant community of artists with technical leanings, but neither were aware of any other accessible opportunities for such open-ended and long-term collaboration. Beecher notes:

> There are plenty of individuals doing one-off sound sculpture performance and installation projects, but not using avenues providing long-term collaborations with research institutions, aside from the MIT Media Laboratory.

English contrasts his ExCITe residency with his subsequent work with researchers at another university.

> It was all off-site. I wasn't doing a residency and I wasn't doing a long-term, close collaboration. There's a potential opportunity, but that feels more like an external project than embedding myself in an institution.

He further indicates a desire to keep pursuing partnerships with research institutions; however, he notes that ideas for collaborative work need to be more developed before initiating a project, suggesting a reluctance of institutions to pursue such collaborative ideation at the earliest phases.

Impacts on Student Outcomes

The projects described above involved a few Drexel students working closely with external artistic collaborators. Many more students at the ExCITe Center are engaged in transdisciplinary projects, often with internal collaborators (other researchers at Drexel). In this section, we examine these overall experiences in comparison with others at the university with regard to research and work experiences. The data presented were obtained in accordance and compliance with the policies of Drexel University's Institutional Review Board (https://drexel.edu/research/compliance/human-research-protection/institutional-review-board/) with the informed consent of individuals (or their parents/guardians as appropriate). Aggregate student data from cooperative work experiences are provided with the permission of the university's Steinbright Career Development Center (https://drexel.edu/scdc/).

Graduate and Undergraduate Student Researchers The student researchers who interact daily at the ExCITe Center have an intimate and detailed perspective of how the space facilitates transdisciplinary work, ideas, and collaboration. We surveyed current and recent graduate and undergraduate student researchers ($n = 14$) across all of the research groups about their perceptions of their research environment. This sample of students was from four different research groups across a range of departments and majors: computer science/engineering, game design and production, electrical and computer engineering, materials science, teacher education, visual arts, psychology,

Table 1. **Student researcher survey data based on a six-point Likert scale from zero (strongly disagree/lowest) to five (strongly agree/highest)**

Statement	ExCITe Center (n = 14)	Other mixed laboratory environments (n = 10)
Uniqueness of research space	4.86	4.00
Transdisciplinary nature of your research	4.36	4.10
Exposure to other academic disciplines	4.43	4.00
Value of your interdisciplinary work	4.07	3.70
Assess your creativity	4.07	3.60
Assess your problem-solving skills	4.07	4.00

mechanical engineering, and design research. To compare the nature of interdisciplinary collaboration between two multi-laboratory research environments, we also surveyed graduate researchers from another space that houses multiple engineering research groups on campus (n = 10). Although the response rate was low, students represented several different engineering laboratories/majors: biological engineering, materials science and engineering, electrical engineering, and photonics (physics).

Student researchers were given a series of six-point Likert scale (zero to five) questions inquiring about the collaborative and creative nature of their work and its relationship to their research space. Interestingly, ExCITe student researchers and the comparison group were fairly close in terms of their perceptions of the interdisciplinary nature of their work. Here, the term "interdisciplinary," especially when applied to student research, may have varying interpretations due to individual experience and access. For example, when asked to elaborate on their most impactful interdisciplinary experience, one student in the comparison group responded that "[it was] a project involving a chemical engineer, a polymer chemist, and an electrochemist." Although this work spans specialized subfields, the transdisciplinary projects at ExCITe focus on connecting more disparate domains, departments, and topics. The research space may shape how one conceives interdisciplinary research, its practical constraints, and potential possibilities.

Conversely, ExCITe students listed their favorite research projects, which included being on stage with drones and a professional dance company, leading STEAM lessons and activities with K-12 students, applying video game knowledge to cyber security, and learning how to be an effective communicator with a wide range of audiences. These responses suggest that students believe that the ExCITe Center is a more unique research environment compared with the other mixed laboratory environments. ExCITe student researchers also perceive themselves as slightly more creative and better problem solvers (Table 1).

In the responses, ExCITe student researchers seemed to value their interdisciplinary work more than the comparison group, and their short written responses reinforced this theme. For instance, one ExCITe graduate researcher noted that an "interdisciplinary project, like an engineer directly working with an artist on a creative tool, has shifted reliable real-world implementation to a higher priority, rather than…just publishing a paper." Contrastingly, one student from the other mixed laboratory environment stated that the interdisciplinary work was a "gift and a curse," and another discussed how it was often challenging to have interdisciplinary projects published in scientific journals.

Additionally, we inquired to see if exposure to different disciplines had altered students' career goals. There was some overlap and agreement between the responses from the two groups of students. Several students mentioned that they are now more aware of applications for interdisciplinary collaborations. Also, they reported being more interested in potential jobs that necessitate cross-domain research personnel. Still, only the ExCITe researchers referenced specific transdisciplinary skills that they have gained, such as STEAM education and the technical and scientific components of arts and music.

Alumni Interviews. We convened a small group conversation between current researchers and two ExCITe Center graduates (both recent PhDs in electrical engineering) who now work at the same large technology company in the San Francisco Bay Area. This reflects the experiences of just two individuals, but the discussion reinforces some of the typical outcomes from transdisciplinary arts–STEM training. Excerpts from this conversation follow.

One alumnus noted how transdisciplinary graduate training prepared them for communicating with a nontechnical audience:

> I did a press interview my first year at [the company]…I know people who have been there for over 10 years that are still asking to do it, and they won't let them.

Both elaborated on how transdisciplinary experience informs their current work on product development.

> At least here [at ExCITe Center, we emphasize] gaining an understanding of product, and working on what that is. Here's *how* this is going to affect people, not necessarily here's the greater number that I can publish for a NIPS [Neural Information Processing Society] paper.

> I think I have [greater] data intuition…We've worked on a lot of projects actually where creativity is an important component of it…[One shipping product] involved building some models where we didn't have data to train anything from.…[Others] would not have the intuition to arrive at what is sort of the right solution to this problem when it's not one of these clean supervised machine learning problems.

They also commented on how arts integration or exposure prepares some differently from other highly credentialed colleagues at their organization.

Table 2. **Co-op exit survey data for the 2016–2017 academic year based on a five-point Likert scale from one (did not meet expectations) to five (greatly exceeded expectations)**

Statement	ExCITe (n = 10)	Drexel (n = 5,558)
Opportunity to demonstrate own initiative	4.30	3.96
Opportunity to develop leadership skills	3.80	3.57
Opportunity for networking and professional development	4.40	3.95
Opportunity for progressive responsibilities	4.30	3.97
Variety of work assigned	4.40	3.73
Quantity of work assigned	4.00	3.57
Challenge of work assigned	4.20	3.53
Training provided by employer	3.60	3.70
Quality of employer supervision/ mentorship	4.10	4.02
Overall job satisfaction	4.20	3.98

> I work with two people who both got PhDs in Astrophysics. . .One of them has amazing intuition and is incredibly great at design and presenting data. . .[It was later mentioned that this colleague also has a background in ballet.] And the other one is more of a hardcore data [person]. . .[This colleague, without an arts background] will build incredibly complicated figures that take 15 min to figure out what's going on one slide, but the results will be great because [they're] brilliant. . .But I think that kind of corners [colleague] in that type of work.

Undergraduate Co-Op Students. The Drexel undergraduate program is distinct from other colleges and universities in its emphasis on experiential, cooperative education (the Drexel Co-Op Program), where full-time work complements classroom learning. Undergraduates complete multiple 6-mo cycles working alongside professionals in industry, nonprofits, government, etc. and receive professional pay. In addition to placing students at companies, the university and its researchers also hire a number of undergraduate co-ops for 6-mo, full-time laboratory work experiences.

To fill its co-op positions, the ExCITe Center seeks students passionate about technology, creative expression, and community engagement. The center is particularly interested in candidates who have prior experience developing and working with new technology (computing, digital media, engineering, and "making") but also have creative interests and pursuits (music, visual arts, dance, and/or design). In selecting student employees, we consider not only their individual skills but also how the skills of all ExCITe co-ops may complement one another. Students who are hired as co-ops are expected to fully embrace the center's ideals of transdisciplinary research and collaboration.

These students are informed that they will be working on a variety of projects and interacting with researchers, students, community members, and even industry leaders of various backgrounds. Individual responsibilities span a wide range of areas: hardware engineering, software development, video game development, media content creation, graphic design, and more (including participation in K-12 outreach programs). Co-ops are encouraged to collaborate with others to address the challenges that they encounter in their projects.

At the end of each 6-mo co-op experience, Drexel students are required by the university to complete a standardized evaluation of their employer. This survey includes both a number of quantitative responses using a five-point Likert scale and freeform text responses to questions. These surveys help inform future co-op students interested in working with a potential employer. In 2016–2017, the ExCITe Center used 10 undergraduate co-op students. In Table 2, we compare mean responses from those 10 student employees with responses from all Drexel co-ops (5,558 students) in the same period.

Responses from co-ops based at ExCITe were higher on average than the Drexel average (the university survey currently does not provide variances for these data, and therefore, we cannot assess statistical significance). In particular, the higher responses to the first four questions ("initiative," "leadership," "networking," "progressive responsibilities") reflect outcomes from other research on cocurricular arts–STEM integrative experiences at

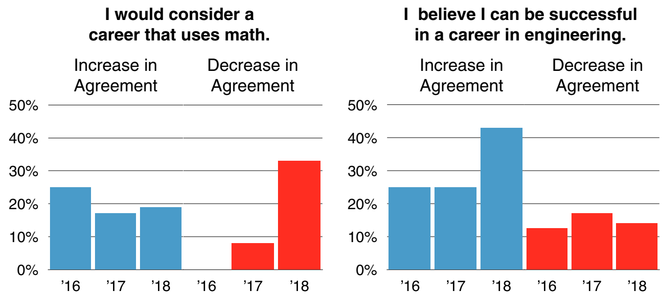

Fig. 3. Changes in perceptions of math and engineering between pre- and postprogram surveys from 2016 to 2018.

the student level (20). In the area of "training provided by employer," it is not surprising to see a lower average, since much of the work emphasizes students finding their own solutions. Admittedly, selection bias (the type of students who apply for and accept these positions) is likely a significant factor.

These outcomes are reinforced in some of the short-answer survey responses from undergraduates. When asked to describe the best features of their employer (ExCITe Center), students wrote the following responses.

> I was shown how my skills as a sound engineer could be used in fields outside the traditional music recording sector. I was given projects where I was encouraged to "think like an engineer" and problem solve independently to see what solutions I could come up with. I got to see revolutionary projects from a behind-the-scenes perspective.

> Being provided the chance to work on a variety of unique projects and solve problems that you wouldn't have the opportunity to do so in typical engineering fields.

Asked of drawbacks or challenges to working at ExCITe, a student replied:

> Sometimes, it can be a little hectic and confusing with the nature of the position. The training and supervision can vary between great and a little light, although this allows for more independence and exploration within the position.

The center continues to collect this set of undergraduate data to better assess outcomes of our 6-mo student employees for ongoing comparisons with other university students.

K-12 Education Programs

Since its inception, the ExCITe Center has offered unique K-12 programs integrating arts and the STEM fields. One reason is that we have generally encountered fewer obstacles (and greater demand) for such interventions at the K-12 level vs. higher education. This is partly due to more widespread interest and support for arts-integrated STEAM education approaches in K-12 settings, which complement other progressive education efforts, such as project-based learning and the maker movement. The center's mission includes STEAM advocacy both locally and nationally. Furthermore, effectively conveying one's research to

Table 3. Scores (mean value for all students within a project topic) based on a rubric with six categories on a four-point Likert scale used to evaluate the students' project presentations

Activity	Design	Knowledge	Application	Presentation	Process	Novelty
Amazing Apps	2.9	3.0	3.0	2.9	2.8	3.2
Custom Controllers	3.3	3.2	3.2	3.4	3.0	3.7
Hardware Hacking	3.3	3.7	3.7	3.0	3.0	3.3
Mechanical Music	3.1	3.2	3.3	3.0	3.3	3.2

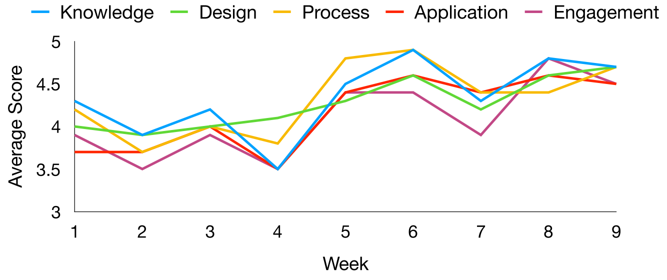

Fig. 4. Aggregated rubric ratings for a 9-wk course on building robotic musical instruments.

a nontechnical audience has always been a priority at ExCITe, and our K-12 programs provide graduate and undergraduate students with a unique opportunity to improve their communication and teaching skills with middle and high school students lacking prerequisite technical knowledge.

The center regularly incorporates work from current research projects into cutting edge workshops and programs for K-12 students, allowing them to explore nontraditional STEAM areas (music technology, video game design, etc.). Since 2007, the Summer Music Technology (SMT) program has introduced rising high school sophomores and juniors in the Philadelphia region to STEAM activities (21). Admitted students participate at no charge, and preferential admission is given to students in the School District of Philadelphia and city residents. The SMT curriculum (lesson plans, activity worksheets, and source code) is made freely available online for other educators' use (https://drexel.edu/excite/engagement/summerMusicTechnology/).

During this 1-wk program, students are guided through several hands-on activities on topics such as loudspeaker design, instrument acoustics, and analog vs. digital representations of sound. For several years, we have collected pre- and postprogram surveys on SMT student participants' attitudes and understanding of mathematics and engineering. Fig. 3 depicts how students' perceptions of future careers in math and engineering are clarified (increases in both agreement and disagreement) during the program. This figure shows that students over multiple years report themselves as being more confident in their ability to be successful in engineering-based careers. It also shows that some of our activities, which require students to use mathematical equations, may need to be revised.

During the week, students also pursue an individual project (guided by a graduate student mentor) from four prepared topics, which we have evolved over the years. In 2016 and 2017, the project options were the following.

- Amazing Apps: develop a custom iPad music app
- Custom Controllers: design a custom electronic music interface
- Hardware Hacking: create a synthesizer or sound effect using digital logic chips and analog electronics
- Mechanical Music: build a robotic musical instrument

All SMT students present their projects during a public showcase at the end of the program. While these are short in duration, many students complete remarkable projects. It is difficult to quantitatively capture the success of these project experiences; in recent years, we have implemented an assessment using four external evaluators (unaffiliated with the program) using a six-category rubric (four-point scale in each category). These results, shown in Table 3, convey an overall evaluation that the projects are of high quality (the average score is over three, where four is the maximum).

In early 2018, the ExCITe Center used the core concepts of the SMT robotic instruments ("Mechanical Music") project to develop a new curriculum appropriate for middle school students. Over the resulting 9-wk mini course developed in partnership with the Science Leadership Academy Middle School, students built simple actuated musical instruments of their own design using littleBits (https://littlebits.com), a set of electronic building blocks, and K'Nex structures (https://www.knex.com). Ten students from the Science Leadership Academy Middle School (a neighborhood school) were split into three groups of three to four students, each led by an ExCITe co-op student. At the end of the 9 wk, students performed a musical piece with their corresponding instruments in a showcase for teachers, parents, and other Drexel faculty.

Each week of the mini course, instructors assessed the middle school teams using a rubric (similar to that used for SMT projects). Fig. 4 provides the average assessments over time, pointing to overall gains in learning (knowledge and expression) over the mini course. Although these ratings were generated by program instructors, they were the ones most familiar with each of the students (and ratings are averaged across instructors). Week-to-week variation (potentially impacted by external factors, such as Philadelphia's Super Bowl victory) reflects a commitment to objective assessment. The success of this pilot enabled ExCITe to commit to the program in future years, where we hope to further refine assessment methodology (Fig. 5).

Conclusion and Future Work

The ExCITe Center is an unusual entity in higher education, an institute developed entirely around transdisciplinary collaborative pursuits with external partners. External artistic and education partners have played a crucial role in these efforts by presenting authentic challenges, contributing unfamiliar perspectives, and providing critical feedback. Although no single project or intervention provides irrefutable evidence of the virtue of such creative collaborations, we believe that the overall portfolio presents a compelling case for the value of such activities at all levels of learning.

Furthermore, we believe that the presented portfolio completes a unique "pipeline" of integrated STEAM learning activities: a middle school course, a high school program, undergraduate courses and research projects, and graduate and postdoctoral research projects (mostly in collaboration with external creative partners). Beyond the integration within activities, the portfolio creates opportunities to integrate knowledge across levels. For example, a project activity (robotic musical instruments) developed for the SMT high school program led to an undergraduate project course (Engineering Design: Robot Symphony), which built the underlying knowledge and systems for a fully staged opera performance of *Sophia's Forest* (some of the control

Fig. 5. Final performance event (April 2018) from the 9-wk middle school mini course.

concepts also informed the Drumhenge project). Additionally, components of this theme were later deployed for the middle school mini course. While the specific tools and technology used at the different levels will vary, the creative concepts remain the same. This mixture of program offerings can create a virtuous circle of experience and inspiration.

In this setting, innovation seldom occurs in a straight path (where advances in one project directly lead to breakthroughs in another). We believe that arts–technology collaborations can facilitate, often indirectly, advances in science and engineering research. This occurs through multiple pathways: from domain-specific insights of artists about the nuances of professional musical performance to new systems and code developed for performances being used to scaffold other research projects. The communications and interpersonal skills reinforced in this environment differ from those generally emphasized through traditional academic training and may enable broader employment opportunities for graduates.

Although this paper has primarily focused on activities integrating the arts (particularly music) with STEM, there is some evidence of increased creative collaboration across the center leading to breakthroughs in research (new awards, joint publications, and the attraction of new students and faculty to the center). One of the most intriguing projects is a fabric-based capacitive touch sensor emerging from a collaboration spanning smart fabrics and robotics researchers (22). It is difficult to imagine such a project emerging without prolonged proximity between fabrics and robotics laboratories. We believe that such efforts will continue to cross-pollinate with other projects internally and externally. The impact of this form of transdisciplinary collaboration across research groups is perhaps even more difficult to measure than the learning-focused outcomes presented in this paper. This remains a topic of intense research interest of ours, and the methods described in this paper represent the foundation for a comprehensive, systematic evaluation process of the ExCITe Center currently in development.

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