Morphing Matter for Teens: Research Processes as a Template for Cross-Disciplinary Activities

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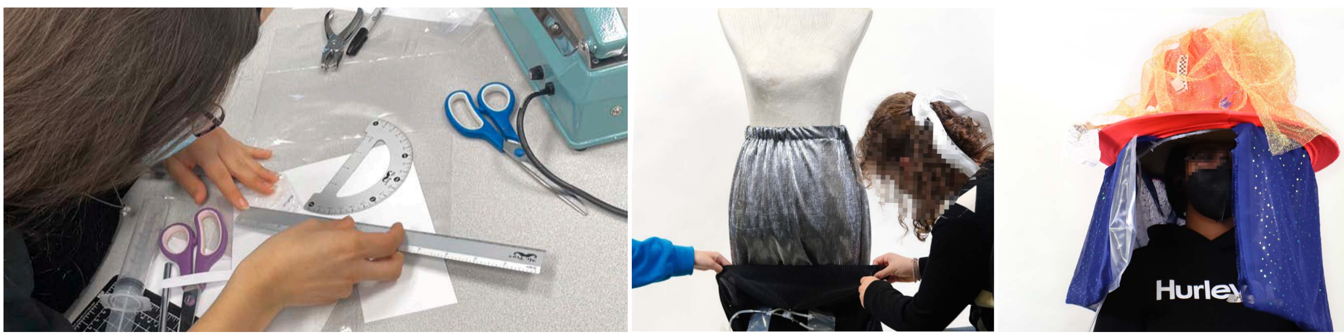

Figure 1: Our teenage workshop participants engaging with morphing matter research processes including material characterization (left) and integrating into fashion objects (center) for personal expression (right).

ABSTRACT

We distilled a set of core practices within "morphing matter" research, derived a set of underlying skills and values, and developed these into a weekend workshop for high-school students. Participants in our workshop sampled a variety of research processes, including materials science and contextual design, incorporating curriculum-appropriate learning goals, toward an integrated pneumatic fashion project. We describe our approach, activity plan, and assessment as well as opportunities for research as an educational template to push beyond current "STEAM"-based educational practices for cross-disciplinary engagement.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

KEYWORDS

Cross-disciplinary learning, research practice

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1 INTRODUCTION

Morphing matter research is a cross-disciplinary domain focused on characterizing and developing complex material interactions for creative and sustainable applications [61]. For example, by reverse-engineering the cellular-level structure of certain seed pods, researchers can construct lightweight deployable actuators that flex and twist reliably in response to changes in humidity [50]. In combining insights from material science, interaction design, mechanical engineering, architecture, computer science and mathematical modeling, morphing matter research is an exemplar domain of future-looking practice.

As a lab focusing on morphing matter research , we were curious how our own research practices could inspire students as well as provide them with both opportunities to strengthen their curricular skills and learn new ones. This paper documents one of a series of workshops for high-school girls (typically ages 14-18) collaboratively hosted by the Morphing Matter Lab in Pittsburgh, Pennsylvania (USA) and Brilliant Labs, an education nonprofit headquartered in New Brunswick, Canada. We focus on a specific workshop in our series which we envisioned as a kind of micro-internship in our lab with the intention of demonstrating key research activities while supporting the curricular goals of high school education. This goal prompted the questions:

(1) What *are* the essential morphing matter research practices, and how do they draw on the component disciplines?
(2) How could we make our methodologies legible to a general audience? Morphing matter is a flourishing research area (subsection 2.1), but it is neither clearly-defined nor particularly visible outside of a handful of research circles.

Additionally, while Brilliant Labs is dedicated to educational outreach in schools and communities, the Morphing Matter Lab primarily does *not* focus on education. While interdisciplinary "making" experiences are well-studied by both practitioners and researchers (subsection 2.2), it is less clear how outside practitioners – experts in interdisciplinary domains, but not necessarily in education or learning – might contribute in an educational setting. Therefore,

(3) How could we corroborate that our plan was grounded in appropriate learning levels for our participants?

To develop our lesson plan, we distilled a set of core morphing matter research methodologies in our lab and others, derived a set of underlying skills and attitudes, confirmed the relevance of these to our audience (high-school students in the USA) correlating them to existing educational standards, and hosted a standalone two-day workshop. By documenting our activity design process, analysing participant outcomes, and discussing possible roles for academic research as an exemplar in primary and secondary education, we make contributions on two levels. First, we introduce morphing matter as an advantageous topic for interdisciplinary learning and provide an adaptable lesson plan incorporating its core processes. Second, more broadly, we contribute a set of methods that other interdisciplinary research labs could use to more confidently collaborate in designing educational research experiences

2 RELATED WORK

Our workshops, and this analysis, draw on past work in inter-, trans-, and cross-disciplinary education, particularly in informal and out-of-school contexts, as well as the landscape of morphing matter as a research domain.

2.1 Morphing Matter Research

"Morphing matter" refers to a class of active materials that can be controlled to change shape, properties, or functionalities due to external stimuli [61]. Morphing matter can be engineered to respond to stimuli including temperature [1], pH [41], moisture [50], pressure [82], and magnetic fields [87]; responses can include changes in shape, texture [47], permeability [58], color [17], or stiffness [24] toward a wide range of functional and experiential goals, including suitability for conventional engineering [13] and bioengineering [44] scenarios as well as day-to-day contexts such as food [77] and clothing [43].

Morphing matter has been studied by researchers in a wide variety of disciplines. Materials Scientists develop morphing materials for challenging contexts [36] and in response to theoretical models [16], and computer scientists apply heuristic and statistical methods to model and predict morphing reactions [85], supporting interactive predictive and inverse design with morphing matter [30]. Architects and designers have used morphing matter for form-finding [5], deployability [27], and adaptive building skins [68]. Within HCI, morphing matter research often focuses on improving accessibility to the field with inexpensive [22, 84] or easy to fabricate materials [78], integrating morphing behavior into specific contexts like fine dining [79], and streamlining the design process with software toolkits [31].

2.2 Making in Education

In preparing interdisciplinary activities for a student audience with the goal of providing a meaningful and educational experience, we join a large and diverse set of initiatives and research projects. Related educational tactics have a long history, from an early emphasis on student self-determination [54] and hands-on learning [83] to the constructivist theory of learning as a inherently participatory process of building knowledge structures [33] and constructionist ideas of learning as physical and material process [60]. These approaches have been particularly manifest in contemporary STEM (Science, Technology, Engineering, and Math) or STEAM (the preceding, with the addition of Art) education, which combines an emphasis on "technological" tools and materials like microcontrollers and digital fabrication with curricular science, math, and engineering education [34] and typically equity-centered values of personalized individual learning (including broadened participation and cultural relevance) [21, 63, 71]. Notably, STE[A]M education often takes place alongside, and often outside, of students' main education context and can introduce students to concepts that are not yet integrated into curricular standards, such as early work on defining computational thinking and how it could be taught [9]. It also frequently takes its cues from the broader "Maker Movement" of adult hobby "makerspaces" and "fab[rication] labs," showing how broader subcultural movements can serve as templates for learning experiences [62]. These values informed our overall goal of supporting an authentic experience with the "real stuff" of research, and they influenced our activity planning, in which we prioritized a blend of hands-on making and group-based discussion and reflection.

With our out-of-school context and de-emphasis on specific quantified learning goals, we are particularly aligned with "tinkering" approaches which center context- and participant-specific trajectories, multi-faceted and open-ended projects, and iterative prototyping as a core mode of engagement [6]. When compared to pure tinkering, the "research as a template" approach documented in this paper involves a relatively high degree of structure: we guided our participants through a planned sequence of activities demonstrating different ways of viewing the overall problem. However, the tinkering paradigm, with its support of fluidity and iteration, was a fundamental aspect of our activities–as indeed it is a foundation of research itself. As such, we base our method of assessment (section 5) on the insights of researchers working in tinkering environments, who observe a variety of indicators of learning more suited to such contexts than quantitative testing assessments would be [64].

However, unlike the researchers behind these works, we are not primarily a makerspace or tinkering studio. Our collaboration between a university research laboratory and an educational nonprofit might be more closely compared to a "visiting artist" [20], albeit for a cross-disciplinary topic. As such, we present our approach to bridging between the research and educational contexts, without necessarily having the expertise or infrastructure of dedicated maker-instructional contexts.

2.2.1 E-Textiles Workshops. In combining textiles with materials research and computational ways of thinking, and particularly in selecting high-school girls as our participant group, our workshop has similarities with e-textiles workshops. E-textiles, also called soft circuits, are an approach to integrating electronic circuitry into textile objects, often either using inexpensive and approachable hobbyist tools and materials, or centering a fiber arts craft perspective. Particularly spurred by work by Buechley et al originating the Lilypad Arduino sewable microcontroller and using it in electronic fashion projects to highlight the importance of aesthetics in engaging a more diverse audience in technology education [10], e-textiles have been proposed as a cornerstone approach for high school educators seeking to promote classroom equity [23], as a tool for breaking up gender bias in computational learning environments [39], and as a way to deepen learners' understandings of computation and how it can fit into their world [73]. E-Textiles and closely related paper circuits have been packaged as educational toys [42], kits [66], and interactive design systems [32] to simplify their deployment in education settings and reach audiences outside of school settings [12, 65]. Research on the relatability and therefore potential everyday inspiration of e-textiles [11], as well as research on e-textiles as a basis for deeper collaborative practice [49], are particularly inspiring for our work.

However, we diverge from core e-textiles approaches in several ways. First, while we did provide optional access to microcontrollers during our workshop, we did not particularly focus on programming or electrical and computer engineering. While morphing matter certainly can include circuitry [80], materials which compute purely mechanically [55] are closer to the heart of morphing matter research than computers per se are. Second, while our workshop culminated in student-driven projects integrating mechanisms into garments, we aimed for the overall experiential locus of our workshop to be the arc of a research journey, balancing the garment integration process as part of an iterative process with complementary activities in gathering data, refining parametric representations of mechanisms, and communicating technical knowledge and conceptual goals.

3 MORPHING MATTER PROCESSES

To use it as a template for an educational workshop, first we needed to understand how morphing matter research works. We had our own intuitions about what our research involved, and we knew that overall, it combines technical expertise from materials science, engineering, computational modeling, and design. However, we did not have a concrete answer to the question "What are the core processes of researching morphing matter?" The first author of this paper surveyed more than thirty papers from our own and related labs, both inside and outside of the HCI research community (including the works listed in subsection 2.1), which were gathered by asking other lab members, including the other authors of this paper, for exemplary works (i.e. "what papers would you show someone if you were trying to explain what morphine matter research is?"). Through reflexive thematic analysis [8], we attempted to identify which processes were "core" by noting which processes recurred most frequently in works that we identified as most exemplary of the domain; this cyclic process involved progressively refining both our selection of exemplars and our conceptual groupings of methods. (For example, is "thinking of possible contexts of use" its own high-level process, or is it most typically part of a broader design phase?) We additionally corroborated our themes by asking the last author (our lab's PI) and senior lab members (graduate students and post-docs) not otherwise involved with this paper to define what "the essential morphing matter research processes" were, and what fields those processes draw upon. To iterate, we reflected on our analysis *alongside* our initial workshop brainstorming: we found that designing specific potential activities helped us refine what was a necessary component of what we came to think of as "the morphing matter research experience." The end result of this process was a set of morphing matter research processes typically (though of course not always) undertaken in this order:

(1) *identifying* an interesting material phenomenon from observation and/or prior work
(2) ***constructing*** material structures integrating the material which exhibit the phenomenon using existing or new fabrication methods
(3) ***characterizing*** its properties via empirical data collection and computational modeling
(4) ***integrating*** it into designed objects by identifying and refining potential contexts of use
(5) *communicating* the work through documentation and presentation

Of these, the core *constructing*/*characterizing*/*integrating* processes are the hallmarks of morphing matter research in particular. A sixth process, common to all research, is carried out in parallel to these:

(6) *evaluating* the work appropriately at each stage

We illustrate how these processes play out in several morphing matter research papers in Figure 2. Different emphases can occur;

for example, the Simulearn system [85] presents an advanced computational model and therefore largely focuses on the *characterizing* process, whereas Patch-O [46] contributes more *integrating*, including studying user-designed applications. However, any project involving morphing matter as we have defined it will necessarily touch on all of these areas.

4 WORKSHOP DESIGN

Building on lessons we learned from running a prior workshop series, we decided to host a two-day weekend workshop for high school aged participants (ages 14-18). Because we were collaborating with a larger effort to bolster STEAM learning in girls, we recruited specifically female students.

4.1 Topic: Fashion and Inflatable Actuators

We chose to frame our workshop around a fashion-based project. In terms of learning outcomes, fashion design incorporates many kinds of challenge, including visual composition, understanding social context, handcraft skills, and soft engineering. Additionally, we hoped that basing our workshop exploration on fashion would support the participants in working on a project that could be meaningful to them.

We chose to center our workshop on inflatable actuators in the style of Ou et al's Aeromorph paper [57]. We show the production of one such actuator in Figure 3: these are airbags made by heat-bonding thin polyethylene plastic sheet, such as plastic sandwich bags, into flat, airtight pouches. Each pouch has a lightweight hose attached via a barb, for inflation, as well as additional sealed inner edges. When inflated, the inner edges constrain the three-dimensional geometry of the overall airbag, causing to bend. In the style of airbag actuator that we initially showed the participants, the sealed inner edges form a diamond shape, and the bending angle of the actuator is determined by the height and width of the diamond relative to the overall airbag. Variant geometries alter the overall shape of the pouch and/or the arrangement of inner edges for a variety of bending, creasing, curling, or twisting effects.

The airbag can be inflated very simply by using a large syringe fitted with a Luer Lock tip to interface with the tubing, or it can be controlled with a microcontroller driving an electric air pump. The tools needed to produce these actuators are an impulse heat sealer, a hot glue gun, and scissors or a hobby knife. The materials are the polyethylene sheet, plastic hose barbs, rubber tubing compatible with the hose barbs, printer paper for selecting masking during the heat bonding process, and some means of pumping air. Overall, this type of actuator is inexpensive to produce, is lightweight and suitable for on-body design, and has a wide range of possible variations.

4.2 Activity Plan

Our overall goal was to lead the participants through processes patterned after our own research. To make the processes legible in such a short timeframe, we scaffolded each to a greater or lesser extent. In particular, since we had pre-selected the airbag actuator as our focus, our **identifying** phase included some explanation of related technical terms like "pneumatics" and "actuator," but was mainly a group discussion of how and why pneumatics, and pneumatic actuators, are used in the world. We additionally started participants off with step-by-step instructions on **constructing** the airbags based on our own accumulated tips and tricks, though we encouraged them to iterate and improve the fabrication workflow as they saw fit. We lead an initial round of **characterizing** as a full-group guided activity, and we structured the early brainstorming and peer feedback portions of **integrating** to keep up the tight pace of the workshop. While the second day of the workshop was primarily about the integrating and communicating processes, we were confident that self-directed returns to each other process would occur as well, due to the cyclic and iterative nature of research. **Evaluation** within each phase was typically guided by questions from us. For example, in the constructing phase, we asked questions like "what problems could make your actuator not work? How could you fix it?"; in the characterizing phase, our questions included "which of the measurement systems we discussed should we use, and why?"

Within this overall flow, we wanted to insure that we touched on a healthy assortment of the skills that tacitly comprise our research processes, as established and practiced in the component disciplines of morphing matter research. For example, empirical material characterization, derived from materials science and mechanical engineering, requires knowing how to use physical measuring implements and algorithmic models, as well as understanding how to assess reasonable data quantity and accuracy. We generated a list of medium-level skills relevant to carrying out each research process, tuned specifically for our pneumatic fashion focus, as well as evaluating the success of that process. These skills are shown as the left column in Table 1.

Within each day of the two-day workshop, we aimed for a range of activity types, from full-group discussions to facilitated breakout activities to hands-on self-directed making time. A summary of our activity plan is in Table 1. In the rest of this subsection, we explain specific activities.

4.2.1 *Initial discussion.*

We opened with a warmup exercise "exemplifying" (as defined by Mayer [51]) the "inflation" concept where participants listed how inflatables are used in the world, and why they are suitable for that use. (For example, an inflatable Halloween costume benefits by being very lightweight; a bike tire or bouncy house benefit from being springy.) We briefly explained some workshop-relevant terms, including "actuator," and discussed examples of how they are used in real-world engineering.

4.2.2 *"Telephone Game".*

After the participants learned how to heat-bond plastic to make an airbag actuator, we used this activity to continue their fabrication practice, while bridging into the characterizing process by getting participants thinking about geometric representations. This exercise epitomized the 'Circle of Viewpoints' and 'See-Think-Wonder' methodologies [70], fostering multi-perspective analysis and critical inquiry into geometric representations. Participants were given five minutes to collaborate with the rest of their table (four tables with three participants each) to produce a written description of the exact geometry of one of the actuators they produced in the first round of constructing actuators. They then rotated descriptions between the tables and had five minutes to replicate the actuator from the description they were given. In a whole-group discussion, participants were asked to compare

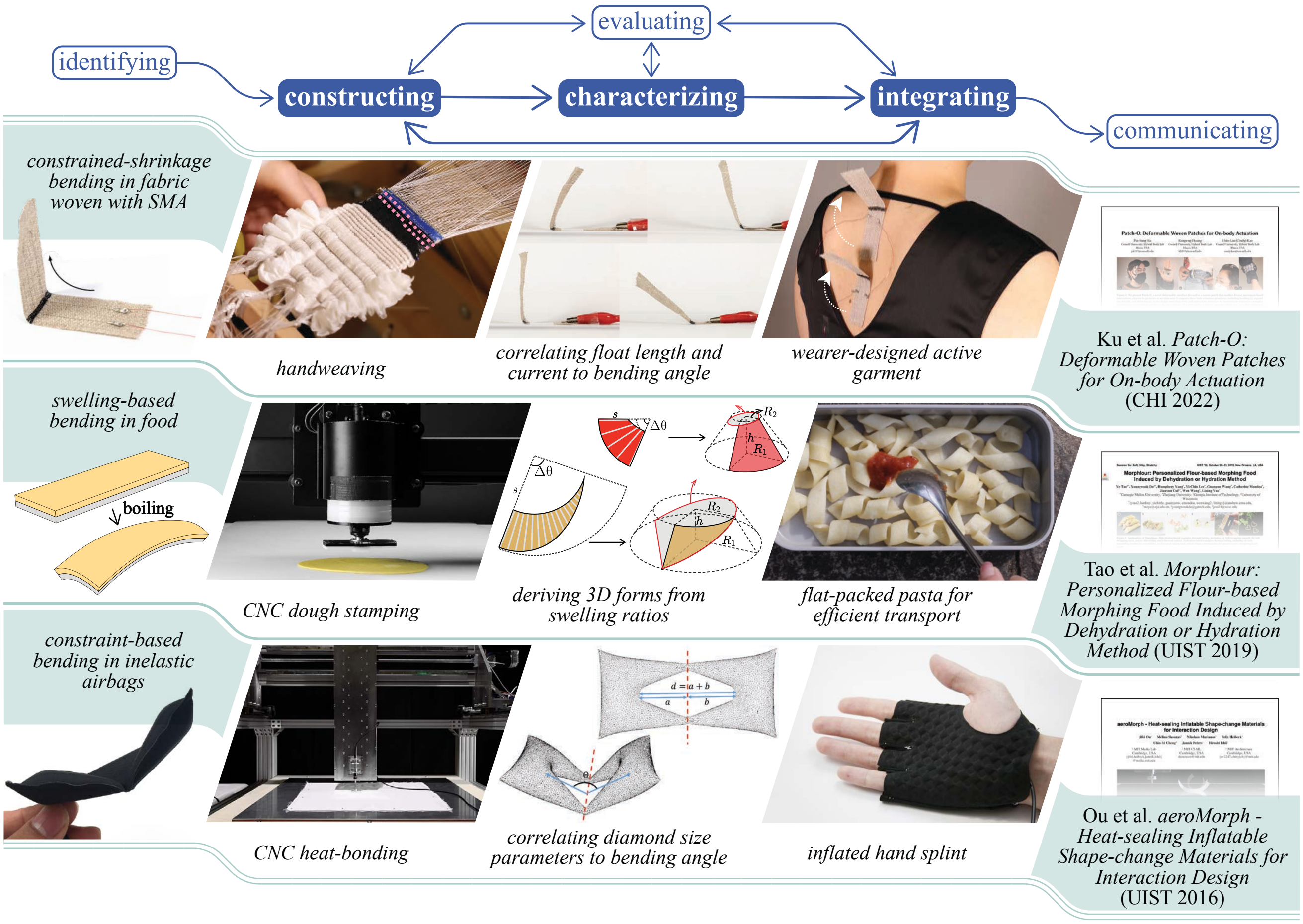


Figure 2: Top: A simplified overview of morphing matter research processes. Below: examples of processes as demonstrated in Patch-O [46], Morphlour [76], and Aeromorph [57]. Images used with permission; ©ACM, 2022, 2019, and 2016 respectively.

original actuators to their replicas and identify which descriptive strategies were effective. Participants then repeated this process of describing and replicating actuators, and we again discussed the results. This activity overall had a high level of engagement and humor, and the participants spontaneously discussed the relative merits of various approaches, such as Cartesian vs polar coordinates and relative vs absolute dimensions.

4.2.3 Material Characterization. To model the process of quantitatively characterizing morphing materials, we facilitated the design of a characterization experiment. We implemented the Predict-Observe-Explain (POE) [25] technique to enhance learning and understanding. Participants first made predictions about how they thought the bending angle would be influenced by the geometry of the interior diamond seal. Participants had, at that point, spontaneously observed that bending angle was influenced by the geometry of the interior diamond seal. We asked participants to work together to determine a more mathematically precise way of describing the relationship. Building on the discussions of coordinate systems and measurement tactics from the Telephone Game, they selected dependent and independent variables, as well as a reasonable data sample size. Together, we decided that each participant would create an actuator of a standard overall rectangular size containing a diamond inner seal with an assigned width (either 4 or 6 inches) and height (either 1, 3, 5, 7, or 9 inches). Participants then measured the maximum bending angle achieved by their actuator and reported it. Afterward, they observed the actual bending angles during experimentation and later explained any discrepancies between their initial predictions and the observed results. Once the bending angles of all the successfully fabricated actuators were reported, we graphed bending angle against actuator height for both widths and showed the data to the participants. This was followed by a group discussion on what trends were observed, how those trends agreed and disagreed with participant expectations, and sources of possible experimental error.

4.2.4 Fashion design presentation. To inspire the participants, we gathered examples of morphing fashion from artists, in fiction, and on the runway. We presented these at the end of the first day of the workshop, when the participants were feeling tired from the day's activities so far, and used them as a basis for a casual full-group

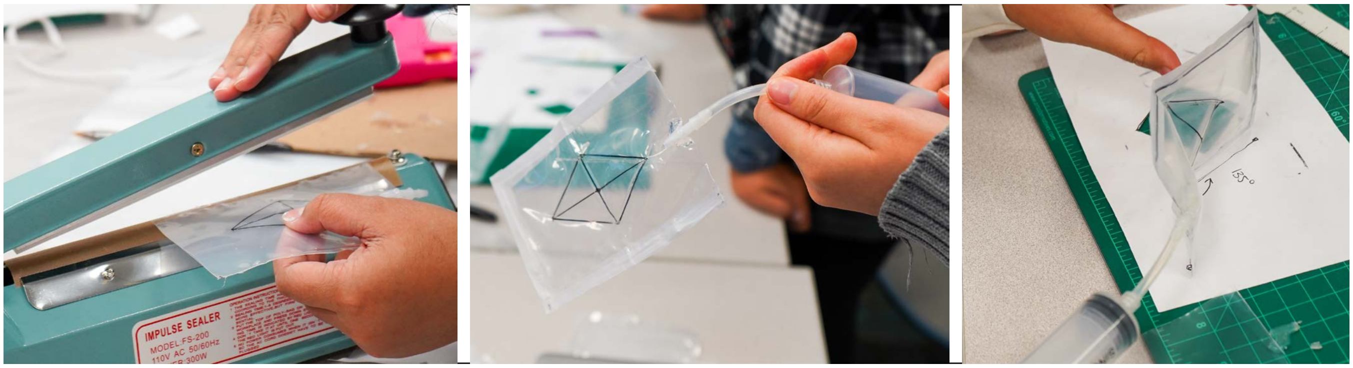


Figure 3: Construction and operation of a "pneumatic diamond-sealed actuator" of the type that we showed the participants how to make, as fabricated by a participant. Left: a heat sealer is used to seal the edges of a rectangular pouch, as well as add interior sealed edges in the shape of a diamond (marked with black marker). A white plastic hose barb is embedded in the bottom edge of the pouch. (We seal the joint between the pouch and the hose barb with hot glue.) Center: the diamond pouch actuator is attached to a large syringe full of air with a short length of silicone tubing. Right: when the syringe plunger is pushed in, the actuator inflates. Because of the diamond-shaped interior edges, the overall shape bends in the middle.

discussion. We additionally briefly discussed some basic elements of fashion design, such as silhouette, texture, and color choices.

4.2.5 Context-based sketching/bodystorming. To direct the participants' efforts in the design portion of the workshop, we asked them to consider the prompt: "For a person who is __, it's a __ that __ when __." Examples: "for a person who is walking outdoors, it's a hood that covers their head when it is raining"; "for a person who is working with ADHD hyperfocus, it is a bracelet that squeezes to remind them to eat."

In a whole-group activity, we went around the circle of participants twice, asking each participant to fill in this prompt with the constraint that they could not exactly repeat previous answers. Next, participants were asked to "sketch" two ideas for a wearable incorporating our pneumatic actuators, drawing inspiration from the brainstorming round if desired. "Sketches" could be either traditional 2D sketches on paper, or bodystormed [72] sketches using gestures or scrap material around their own or a colleague's body, and participants were given ten minutes to work on this. Lastly, we gathered for whole-group feedback and ideas-sharing. The feedback session was introduced with a brief presentation on giving good feedback.

4.2.6 Prototyping/Fabrication Time. Participants were given three hours to select and prototype [67] one idea from the sketching activity, either individually or as part of a group. We provided participants with textile materials, including raw fabric as well as thrifted garments to modify, and inflatable actuator components. They were also given the option to integrate simple electronically controlled air pumps into their projects. Participants were permitted to bring in personal materials and tools; at least one participant brought in her own sewing machine, and another brought a sewing kit with scissors and other tools. Participants were asked to document their process and were given the option of printing photos they had taken either with their phones or with the dedicated photography booth in the workshop to use on their poster.

4.2.7 Presentations. The workshop culminated in a set of presentations of the prototypes and the documentary posters. Because we see communication as an important research process, we emphasized the presentations by first drafting and practicing them in small groups, then giving a first presentation to the overall group of their peers and the workshop facilitators, before ultimately presenting to an audience of any guests they wished to invite (i.e. their parents/guardians).

4.3 Alignment to Learning Standards

As primarily morphing matter researchers, not educators, we did not have a firm understanding of current curricular expectations. To check that our lesson plan would likely be at a level of challenge that was exciting but not overly frustrating (the "zone of proximal development" [52], and to understand how morphing matter processes might be relevant to our participants' overall learning, we decided to look to *learning standards. Learning standards are educational guidelines that outline the expected knowledge and skills students should acquire at various stages of their education. These standards serve as foundational elements for schools in formulating curricula and assessment frameworks across various grades and disciplines. They are typically established and published by either governmental or non-governmental organizations, such as professional teaching associations, within a particular geographic region.* Under the guidance of our educator collaborator, we examined a variety of locally-relevant standards:

- Pennsylvania Department of Education Standards Aligned System [15]: a set of state-wide standards which build upon the national Common Core State Standards Initiative overseen by a US national political organization and covering English language and math education. In our state, these localized Common Core standards include additional topic areas such as "Business, Computer and Information Technology" and "Science and Technology and Engineering Education." (We found the latter most relevant to our research

identifying
- Observing specific material phenomena in the world
- Theorizing how existing natural and artificial mechanisms work
- Connecting technologies to contexts of use
- *Relating to prior work*

constructing
- Using fabrication tools and techniques
- Improving production processes
- Fabricating a structure to a specification
- *Identifying and fixing physical problems (e.g. leaks)*
- *Observing and communicating successful fabrication tactics*

characterizing
- Deriving shapes from verbal descriptions and vice versa
- Establishing geometric references such as coordinate spaces, datum planes, and units of measurement
- Generating hypotheses and identifying experimental variables
- Describing geometry parametrically
- *Making angular measurements*
- *Comparing methods of quantitative representation*
- *Assessing data in chart form*
- *Identifying appropriate levels of precision*

integrating
- Describing conditional deployment
- Identifying contexts of use
- Sketching ideas visually or gesturally
- Building on peer ideas
- Integrating active elements within overall material structures
- *Noticing, articulating, and using artistic conventions in fashion*
- *Identifying a feasible project and shifting scope as necessary*
- *Iterating and debugging complex mechanisms*

communicating
- Documenting process and outcome
- Using technical terminology related to active materials (inflation, pneumatics, actuation, and deployable structures)
- Communicating technical aspects, design concept, and context
- *Giving constructive feedback*
- *Refining communication in response to feedback from peers*

Day One

Discussion: Where and why do we use inflatables? What is an actuator?

Demonstration and Hands-on: Diamond curvature actuators and how to make them with the heat sealer

Discussion: How to diagnose and fix problems with the actuators; tips and tricks for fabrication; which 2D parameters affect 3D shape

Guided activity: "Telephone game" of describing and fabricating specific actuators

Discussion and Hands-on: Designing an experiment to characterize shape change; fabricating new actuators; gathering data

Discussion: Interpreting material characterization data and its accuracy. How could we do better?

Presentation and discussion: Ou et el's Aeromorph and other modular inflatables

Presentation and discussion: Fashion design and actuated clothing in art, design, and industrial applications

Day Two

Guided Activities: Brainstorming concepts for actuated wearables for specific contexts of use; sketching/bodystorming concepts

Discussion: Sharing ideas and providing feedback; refining concepts

Hands-on: Building integrated inflation-actuated wearables; refining concepts to fit the time; debugging complex behaviors

Guided Activities: Documenting projects visually and verbally; presenting the work to the rest of the group, then to invited guests

Table 1: Left: skills associated with morphing matter research processes. ("Evaluation" skills, which exist within each of the other skill categories, are italicized.) Right: a summary of our activity plan.

skills.) These are arranged by grade level and presumed course context.

- National Core Arts Standards (NCAS) [74]: a set of eleven "anchor standards" across four activity modalities (creating, performing/presenting/producing, responding, and connecting) with assessments for each standard at each major age range in each of a variety of media, performing, and visual arts. NCAS is produced by a coalition of arts and arts education organizations in the USA.
- National Science Teachers Association Next Generation Science Standards (NSTA NGSS) [56]: a comprehensive K-12 science education framework emphasizing inquiry-based learning and real-world applications. Each NGSS "performance expectation" is associated with a "crosscutting concept," a "science and engineering practice," and a "disciplinary core idea," within four science domains and across age/grade ranges. NSTA is a professional organization for science educators.
- International Society for Technology in Education (ISTE) [37]: sets of standards for students, educators, education leaders, and coaches with the aim of promoting effective technology integration in education to enhance student and

Using fabrication tools and techniques	Learning to use tools, materials, and artistic conventions	**Studio Thinking** Develop Craft Technique
Fabricating a structure to a specification	Follow precisely a multistep procedure when carrying out experiments, taking measurements, or performing technical tasks.	**Common Core** RST.6-8.3
Establishing geometric references such as coordinate spaces, datum planes, and units of measurement *Comparing methods of quantitative representation*	Evaluate merits and limitations of two different models of the same proposed tool, process, mechanism, or system in order to select or revise a model that best fits the evidence or design criteria.	**NSTA NGSS** Developing and Using Models
Generating hypotheses and experimental protocol *Describing geometry parametrically*	Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems.	**NSTA NGSS** Developing and Using Models
Generating new inquiries *Identifying experimental variables* *Identifying appropriate levels of precision*	Make a quantitative and/or qualitative claim regarding the relationship between dependent and independent variables.	**NSTA NGSS** Constructing Explanations and Designing Solutions
Making angular measurements *Recording data and charting it* *Describing geometry parametrically* *Assessing data in chart form*	Use mathematical, computational, and/or algorithmic representations of phenomena or design solutions to describe and/or support claims and/or explanations; create and/or revise a computational model or simulation of a phenomenon, designed device, process, or system.	**NSTA NGSS** Using Mathematics and Computational Thinking
Identifying contexts of use *Sketching ideas visually or gesturally*	Students know and use a deliberate design process for generating ideas, testing theories, creating innovative artifacts or solving authentic problems.	**ISTE** Innovative Designer (1.4.a)
Describing ideas to peers *Communicating design concept and context* *Building on peer ideas*	Engage in constructive critique with peers, then reflect on, reengage, revise, and refine works of art and design in response to personal artistic vision.	**National Core Arts Standards** Visual Arts: Creating: Reflect/refine/continue (VA:Cr3.1.IIa)
Identifying a feasible project scope *Reflecting on concepts* *Iterating physical prototypes* *Integrating active elements in overall structures* *Debugging complex structures* *Shifting concept or scope as necessary*	Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.	**NSTA NGSS** Constructing Explanations and Designing Solutions
Giving constructive feedback	Examine and evaluate various types of critical analysis of works in the arts and humanities: Contextual criticism, Formal criticism, Intuitive criticism	**Common Core** Arts and Humanities: Critical Response (9.3.12.E)
Documenting process and outcome	Document the process of developing ideas from early stages to fully elaborated ideas	**National Core Arts Standards** Visual Arts: Connecting (VA:Cn10.1.Ia)
Communicating technical aspects of the project	Communicate scientific and/or technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically).	**NSTA NGSS** Obtaining, Evaluating, and Communicating Information
Identifying contexts of use	Making works that convey personal meaning and interpreting meaning in the works of others	**Studio Thinking** Express

Table 2: Left: morphing matter research skills from Table 1. Center and right: relevant US high school learning standards and their sources. Yellow highlights indicate the themes we track in subsection 5.1.

teacher proficiency in the digital era. The ISTE "Student" standards are arranged by cross-cutting roles, such as "Innovative Designer," "Computational Thinker," and "Creative Communicator." ISTE is a nonprofit organization originating in the USA.

- Studio Thinking [48]: a framework organized around habits and structures that support studio arts practice, developed by a small group of independent arts education researchers.

Most of the learning standards in our region focus either on a particular subject (e.g. NSTA NGSS, National Core Arts Standards) or context (e.g. Common Core is meant for classroom based learning), so we opted for a combination of standards from varying disciplines to appropriately characterize the learning goals of the workshop. In Table 2, we show how our morphing matter process skills align to learning standards from these sources.

4.4 Participants and Data Collected

We recruited via email to local schools and after-school programs. We had twelve participants, of which ten stayed for the entire workshop. (One left early on the second day and the other was unable to attend on the second day due to a family emergency.) Demographic and prior experience information is shown for the ten full participants in Table 3.

Of note, participants P6, P7, and P10 had a prior friendship. Participants P8 and P9 were home-schooled sisters, and the other participants came from six different local high schools. As mentioned in section 4, because our workshop was held as part of a larger effort toward STEM outreach for girls, all of our participants were female (self-identified).

4.4.1 Selection and Participation of Youths. We ran our workshop in Pittsburgh, PA, USA. Our participants were minor teenagers in grades 9-11 (ages 14-17). We recruited via email sent to contacts at local high schools and after-school activity centers and accepted all participants who registered. Our recruitment materials described our workshop as "for high school girls" but we did not otherwise enforce age or gender requirements. Each participant and their guardian read and signed a 4-page, plainly-written consent form agreeing to confidential audio and video recording and anonymous data reporting, and acknowledging the possible risk of injury from working with physical tools and processes. Our workshop was run without monetary compensation or cost to the participants. We provided lunch and snacks to the participants on both days.

4.4.2 Data Collected. We captured audio and video recordings of group discussions, presentations, and each table work area. We collected images of the artifacts produced by the participants, including in-progress work, sketches, and the photographs the participants produced themselves during the documentation part of the workshop. At the beginning and end of the workshop, participants took brief written surveys which queried their attitudes toward, and experiences with, relevant skills and topics. We conducted brief one-on-one semi-structured interviews with each participant at the end of the workshop. (Two participants left early on the second day of the workshop and are elided in our data.)

5 ASSESSMENT

Assessing participant learning in an interdisciplinary and freeform environment can be difficult [3, 64]. The breadth of topics we touched on would make for an unwieldy post-exam, and we considered formal assessment less relevant for our out-of-school context. Instead, we focused on assessing how the students engaged with our topics and activities. One possible metric of engagement is simple participation: did each participant complete each activity, without excessive prodding by instructors? We found this metric not particularly satisfying; due to the structure and voluntary nature of the workshop, all of our attendees participated in all of the main activities: each participant made their own test airbag, helped gather data in the characterization activity, contributed ideas and feedback to the brainstorming session, and ultimately produced a project solo or in a 2- or 3-person team. Even the relatively dry "data-gathering" activity had good participation, with one participant even discovering a methodological flaw in the characterization procedure, and another noticing and fixing faulty data. Other than one participant who had a family emergency, every participant returned for the second day of the workshop.

In addition to being a fairly low bar, and difficult to extrapolate from the sample size of a single workshop with fewer than fifteen participants, simple participation does not elucidate participant experiences, outcomes, or the effects of using our research processes as a template. Did the participants find the activities memorable, and were their experiences relevant to their overall learning? How did their own cross-disciplinary interests and aspirations influence their perceptions of, interactions with, morphing matter research processes? We address the first question in subsection 5.1 and the second in subsection 5.2.

5.1 Salience of Learning Goals

Building on the curricular relevance demonstrated in subsection 4.3, we wanted to understand the morphing matter research skills' salience to our actual participants. To do so, we analyzed participant narratives of their project and experience *in their own words* through two sources of self-narrative data: their oral project presentations and our one-on-one post-workshop interviews. (The post-workshop survey was largely multiple-choice/Likert-scale questions, not the participants' own words.)

As described in subsubsection 4.2.7, the participants gave presentations thrice: once as an initial practice attempt in small groups, a "first round" for the whole workshop group, and "second round" in front of a small audience of invited guests. The presentations were generally more succinct for the final audience, averaging about two minutes in the first round, with an additional two minutes of questions per project, a minute and a half for the second round. Because some participants worked in groups for the final project, not every participant spoke in all presentations. In the three-person team, P6 and P7 co-presented for the first full-group round, and P10 presented for the guests round. Additionally, P5 presented her joint project with P11, who had left just before presentations. Two participants (P11 and P12) left before presenting or being interviewed, and are therefore not included in this analysis.

Our semi-structured post-workshop interviews were limited by their brevity, lasting an average of five minutes. This length was constrained by the relatively small number of our team trained to give interviews and the available time at the end of the two-day workshop. The post-survey given just before the interviews asked for feedback on individual activities and thus likely reminded the participants about what they had done, but the oral interview questions did not reference specific activities or learning goals. Instead, we asked these high-level questions:

- What skills and techniques do you feel you learned?
- Was there anything missing that you wanted to learn, but we didn't cover?
- Do you feel confident that you will be able to apply the skills you learned in this workshop in the future?

	I am familiar with...													I am interested in...														age	hobbies and interests
	Morphing Matter	Inflatable Fashion	Pneumatics	Procedural Design	Digital Fabrication	Measuring/Scaling	Physical Computing	Robotics	Actuated Textiles	Data Analysis	Hypothesis	Design Critique	Microcontrollers	Arts and crafts	Material Science	Geometry	Engineering	Digital Fabrication	Physics	Chemistry	Digital Skills	Programming	Design thinking	Culinary Arts	Fashion design	Photography/video	Interior Design		
P1											■			■		■		■		■			■	■	■		■	14	art, music
P2												■		■									■		■			16	running, sewing, drawing, learning about fashion
P3	■	■		■	■	■	■		■	■	■	■		■	■			■			■		■		■	■	■	17	sewing, creating art, reading
P4			■					■		■	■	■	■	■			■	■	■	■	■	■	■	■		■		16	robotics team
P5								■			■					■	■											15	dance, robotics, reading
P6						■				■	■			■				■					■	■	■	■		15	video games, drawing, reading and writing, comic books
P7						■				■	■			■				■		■	■		■	■	■	■	■	15	reading, writing, drawing
P8						■				■	■			■						■				■	■			14	painting and listening to music; reading, doing makeup, reading about fashion, and learning about astrophysics
P9						■				■				■			■	■	■	■	■	■	■	■				16	reading, biking, and sometimes sewing; the immune system, outer space, and various random interesting facts
P10			■					■						■	■		■	■		■		■			■			15	dance, reading, art related things, "(lots of yarn and paint)"

Table 3: Participants' hobbies and interests from the initial survey. "I am familiar with" and "I am interested in" were presented as "choose all that apply" checklists. Hobbies and interests were free text and are lightly paraphrased here for brevity.

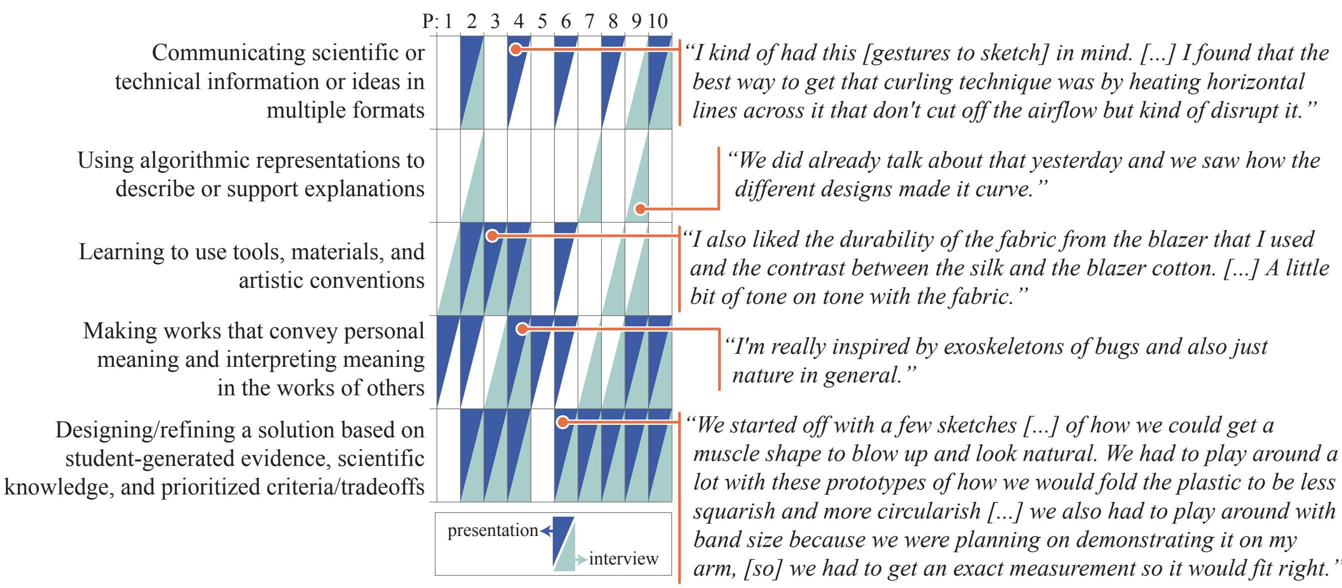


Table 4: Instances of learning themes referenced in student project descriptions and post-interviews. A filled triangle indicates at least one supporting comment.

- What do you see yourself creating using the skills you learned in this workshop?
- Do you feel satisfied with the project you created?
- Do you think you will try something like this in the future? Either to make projects at home or in school / as a job?

We don't assume that participant self-reports of skills learned are necessarily accurate; however, their responses could point toward what was new, exciting, or relevant to the participants.

To structure our analysis, we selected a subset of evaluation criteria from our list of relevant learning standards (Table 2). We prioritized criteria that were particularly relevant to morphing matter research, that cut across disciplines, and that were not explicitly enforced by us (e.g. not "Document the process of developing ideas from early stages to fully elaborated ideas" because we specifically told them to do so).

For each selected goal, we looked for instances of each participant either mentioning a related activity directly, or describing their experience in a way that shows evidence of learning in that area. For example, for the goal **"learning to use tools, materials, and artistic conventions,"** P1, P3, P8, P9 all specifically recollected "learning to use the heat sealer" in their interviews (direct mention), and P7 discussed her team's incremental understanding of how to work with heat-sealed plastic, noting that "the material was hard to fold once it was already stapled down. So I might cut it into different pieces and then press those all together" (evidence of learning).

We present an overview of this data in Table 4.

Unsurprisingly because it was the focal activity of the workshop and the topic of the presentation, **"Designing/refining a solution based on student-generated evidence, scientific knowledge, and prioritized criteria/tradeoffs"** is well-represented: most participants mentioned how they designed and refined their pneumatic wearable with an eye toward tradeoffs and what they understood about diamond-inflatable actuator design. Especially within the presentations, participants mentioned factors influencing their results including time constraints, successful or failed prototypes, and how actuator motions would ideally cause their desired results. Participants particularly described their workarounds for assembling their project quickly (e.g. P2 used safety pins instead of sewing, and P9 made a deliberately partial prototype) and their processes for location and fixing holes in their air bags, indicating that they were particularly involved in troubleshooting and problem-solving processes.

Every participant – even P5, who was quite taciturn – touched on **"making works that convey personal meaning and interpreting meaning in the works of others"** at least once, whether in their presentation or their interview. We hypothesize that this is partially influenced by how we structured the initial brainstorming of the projects, which emphasized user and context. However, some of the "purposes" were deliberately exaggerated to the point of comedy for personal joy (e.g. an octopus-shaped sun hat, because P9 wanted to make something big), and even projects that weren't explained as having a particular "purpose" were connected to something relevant to that participant (e.g. P4's morphing skirt, because she is inspired by beetle exoskeletons).

Very few participants mentioned or invoked **"using algorithmic representations to describe or support explanations"** within the presentations or interviews. The strongest recollection was P2, whose commentary was still fairly lukewarm, noting that "it was a little bit difficult for me, but I was still able to do it." This is in contrast to the reality that every participant did, in fact, participate in both the Telephone Game and main characterizing activities, with many spirited discussions especially during the Telephone Game, and participants engaged enough to call out errors in a proposed methodology (P9) and question/double-check specific data points (P6 and P7). Participants also clearly used their understandings of Ou et al's identified parameters in refining their projects; for example, by adding more diamonds to produce more cumulative bending. We hypothesize that these activities may have been the least novel, or most school-like, and therefore least salient or interesting to most participants. Additionally, in the presentations, participants tended not need need algorithmic representations because they could simply use visual or gestural descriptions (e.g. "it bends like this"). Lastly, while we were focusing on the physical/geometric representation in this analysis, we observe that participants did tacitly incorporate the inherent time dimension of morphing matter into their presentations; for example, all three posters of our case study participants (Figure 4) include "before and after" sequential imagery.

5.2 Case Studies: Ways of Engaging with Research Processes

We were curious how students' own cross-disciplinary interests and aspirations influenced their perceptions of, and interactions with, morphing matter research processes because STEAM education, particularly in e-textiles, is often positioned as a basis for positively shaping student aspirations and improving transfer across knowledge domains, particularly for minoritized students such as girls in electrical engineering [11] However, we noticed that many of our participants *already* self-defined as multidisciplinary learners with a wide variety of interests and aspirations. Many of them had done similar blended projects before, though not necessarily framed as research.

To better understand how participant backgrounds and aspirations influenced their experiences with the various research processes, and to understand how learning or inspiration could be supported, we document three case studies [86]: one group of three friends who chose to collaborate on their final project, as well as two individuals. We chose these three cases because, together, they provide good representative coverage of the overall participant group: different ways of working, different priorities, and different backgrounds.

Our analysis in this section is based on participant survey data (pre- and post-workshop), the post-workshop interviews, our audio/video and photographic recordings of the workshop and the artifacts produced, and our instructing team's observations of the participants both during the session and in reviewing the recordings. To help spur and structure the instructor observations, we considered the four types of indicators of learning in "tinkering" environments proposed by Petrich et al. – *engagement*, *intentionality*, *innovation*, and *solidarity* [64] – as a prompt. To summarize Petrich et al., indications of *engagement* include "expressions of joy, wonder, frustration, and curiosity," and "work inspired by prior examples"; *intentionality* is evident in variation, personalization, and self-direction toward projects and efforts; *innovation* includes "repurposing ideas/tools," deliberately "redirecting efforts," and "complexification of processes and products"; *solidarity* can be shown in borrowing and sharing "ideas, tools, approaches" and "helping others to achieve their goals." For each, we asked each member of the instructing team for examples of each of our focal participants showing that indicator. These examples included some recollected anecdotes, as well as corroborating evidence from our recorded data. We used Google Sheets [28] to sort and analyze the survey data and Dovetail [35] to transcript, tag, and cross-reference the

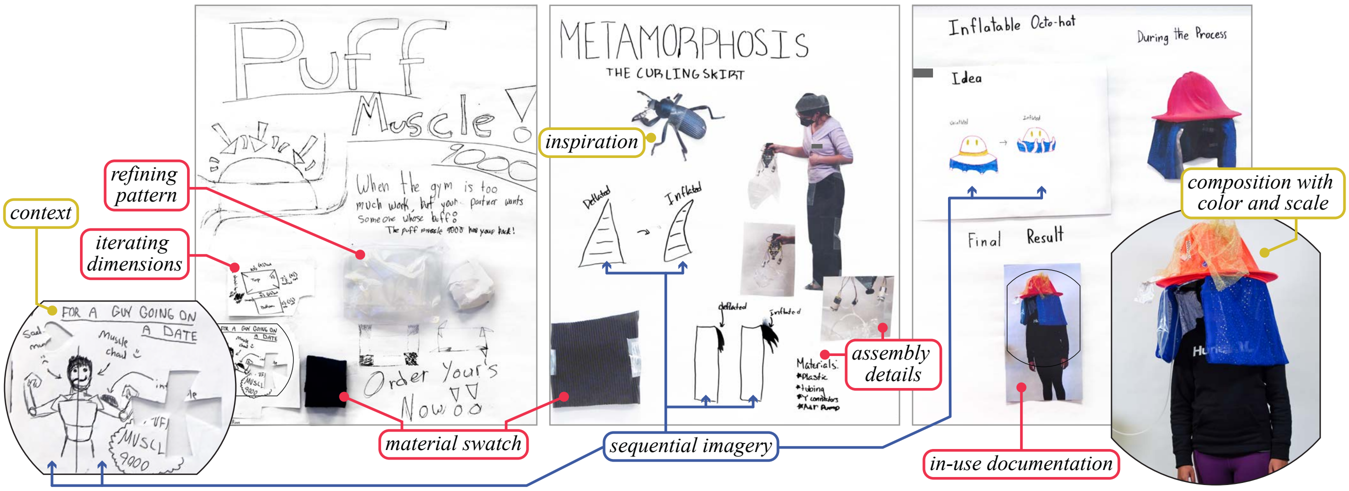


Figure 4: Presentation posters from the participants discussed in subsection 5.2. Left: the Puff Muscle 9000 by Team Puff Muscle (P6, P7, and P10). Center: The beetle-inspired Metamorphosis Skirt by P4. Right: the Inflatable Octo-Hat by P9.

recording and interview data. All authors of this paper contributed to tagging the data, which was done iteratively, with each data source processed by at least two and typically three members of the team. Initially, we tagged based on learning goals, participant reactions (such as "wants to learn more" or "isn't sure why this would be useful"), and each author's discretionary highlighting of incidents worth discussion. As we periodically discussed emergent patterns, we re-visited the data to synthesize the tags into thematic codes to develop our "ways of engaging research processes" thematic framing for understanding the participant experiences.

5.2.1 Team Puff Muscle (P6, P7, and P10). Three participants had an existing friendship – P10 and P6 mentioned that P7 recruited them to join the workshop. P7 mentioned in her interview that she had looked up the definition of "actuator" to explain what kind of workshop it would be to a friend (though it's unclear whether the friend in question was one of the participants or not). These three–P6, P7, and P10–worked together on their final project, the "Puff Muscle 9000" artificial bicep allowing its wearer "to be buff without having to go through the struggles of going to the gym."

All three team members showed *engagement* throughout the workshop, as active participants in all of the activities including asking technical questions during the fashion inspiration presentation at the end of the first day (at a time when everyone was getting tired). Team Puff Muscle's *intentionality* showed in both the humor and technical aspects of their project. They had a clear narrative for the Puff Muscle 9000, which they "sold" with self-directed infomercial-like language and joking claims from their initial design sketches through the final presentations. They were also intent on solving technical fabrication problems. They worked together on numerous techniques to debug a persistent leak in their pneumatic actuator, including using much of their snack break time to do so. They ultimately ran out of time before fully solving the problem, and all three team members were still musing about possible solutions to their leak during both the presentations and their individual post-experience interviews. In the post-survey, P6 and P10 mentioned the air leak as the most frustrating part of their project. However, it wasn't a fully negative experience: when asked to rate their comfort with debugging and problem-solving on a scale from 1 to 5 (with 5 being the best) all three members of Team Puff Muscle responded with a 5 during the post-survey, whereas P6 and P10 had responded with a 4 for the same question in the pre-survey.

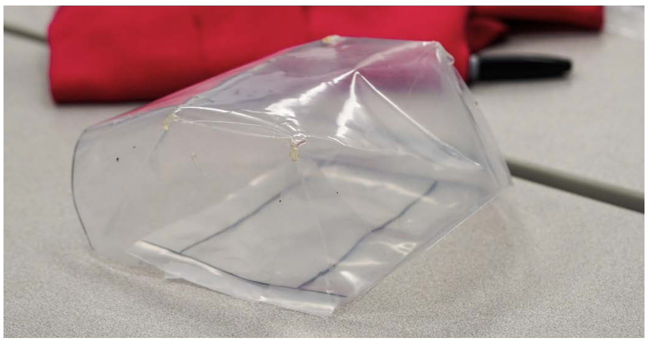
They showed *innovation* in choosing to build a different kind of pneumatic actuator than the one we taught: instead of a creased bending actuator, they produced a pillow-like airbag which drew on P10's understanding of sewn object shaping to incorporate heat-sealed darts for a rounded shape.

Team Puff Muscle's primary *solidarity* was within the team – in P10's summary, "[P6] came up with the main idea of it all and then me and [P7] kind of figured out how we were gonna connect all the corners and I was the one who had the most proficiency in sewing skills. So I mainly focused on the arm band, then connecting it to the arm band while the other two focused on constructing it and filling up any holes" – but they were broadly outgoing in engaging other workshop participants as well. They were also especially active in providing feedback and discussion during the design critique activity on the second day, and in helping other participants with leak-debugging.

P10 was particularly enthusiastic about interdisciplinary work. She had a demonstrated and discussed interest in technical sewing and historical fashion. When asked whether she could see herself in a lab like ours, she mentioned that her career aspirations were likely science-based ("biology and like a more medical field or like chemistry"), but that "the more I go to internships and workshops like this, I'm like, wait a second, I want do too many things in life. There's too many cool things. [...] I had no idea that there were labs that did this and I'm so happy that they exist."

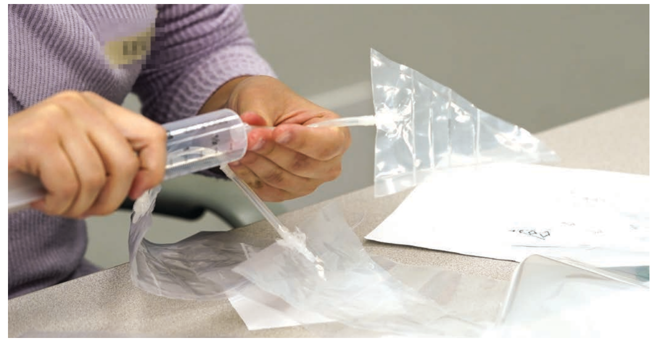
P7 listed her potential college majors as "business and fashion," though she also said that her reason for taking the workshop was "I'm going to start sewing soon and getting used to fashion." (In her post-survey, she rated the helpfulness of this workshop for her

(a)



(b)

Figure 5: Team Puff Muscle. (a) The team attempting to debug their leak. One member of the team is using the microcontroller pump to add air and another is standing by with a hot glue gun. (b) A prototype puffy airbag showing sewing-style three-dimensional shaping.



(a)

(b)

Figure 6: P4 working on her curve actuator. (a) She tests one module with the hand syringe. (b) She has hooked up several modules to the microcontroller pump. She directed the taking of these sequential images (deflated and inflated) and used them as part of her poster documentation.

career as a "3," which may indicate that she didn't find it particularly fashion-based.)

Team Puff Muscle's collaboratively interdisciplinary approach showed finesse in how they balanced/bridged interests, and it therefore exemplified **research as a way of building things together**: bringing together ideas and techniques that might not otherwise be combined.

5.2.2 Metamorphosis Skirt (P4). P4's project goal was a bio-inspired "Metamorphosis" skirt ("like Kafka's bug"), which could unfold like a beetle's wings ("a cool spooky bug abdomen"). She included a swatch of fabric in her final poster to help communicate the overall vision, but she focused on prototyping the actuator component instead of the whole skirt.

Because of this scoping decision, she was able to finish relatively early. She used the extra time showing *solidarity* in assisting P2 with her project, and refining her poster more than other participants had time to do. In her poster, she *innovated* in including printed imagery of her beetle inspiration and in using photo cut-outs in her composition (which inspired P9).

P4's tight project scope and specific visual concept show *intentionality*, and she *engaged* with the previous day's activities by using different sealing patterns from Ou et al as the basis of her experiments to refine the specific full-but-curved shape she had in mind. In addition to refining her specific sealing pattern for her desired shape, she pushed the technical construction aspects of her project by using two of the "optional" construction techniques we supported: 1) attaching multiple airbag modules together with branching tubing connectors, and 2) using the microcontroller air pump for inflation (needed because of the relatively higher volume of air required for multiple modules).

P4's background includes a love of science and math, but a broad range of other interests as well, with above median "interested in" and "familiar with" items in the pre-survey (Table 3). She participates in a university-hosted robotics club and listed "both mechanical and electrical engineering" as possible college majors for herself. The instructors perceived P4 as quite savvy about research methods and robotics, perhaps because of her background. While she never directly mentioned it, her bio-inspired concept was well-aligned with much existing morphing matter research (e.g. [26, 81]) and may indicate outside familiarity with our lab and related work. However, her results with the project were not just prior knowledge. For the self-rating "I feel comfortable using pneumatics to design projects" (1-5, with 5 being the most comfortable), P4's pre-workshop assessment was 3 and post-workshop was 5; that is, she learned much more about constructing pneumatic circuits than she knew before. Instead of benefiting from specific operational knowledge, it is likely that she had an understanding of research mindsets and priorities.

In approaching a specific concept-driven aesthetic with tactical iteration building off of prior work; P4 undertook **research as a set of methodological tactics and conceptual goals**: a way of making connections to other scholarship and being thoughtful, at the process level, about desired outcomes.

5.2.3 Octopus Hat (P9). P9 attended alongside her sister, P8. Both are home-schooled. P9 joined the workshop with a clear desire to learn and explore. She is particularly excited about science – her favorite subjects in school are "Math, Biology, Chemistry and Physics" – but her interests are broad; for example, she listed "reading, riding my bike, and sometimes sewing" as hobbies and "the immune system, outer space, and various random interesting facts" as favorite topics. In conversation, she brought up her burgeoning interest in fashion design as well.

P9 was highly *engaged*, correctly identified a procedural error during the "characterization" activity, and contributed many relevant facts and theories to the various discussion activities, including connecting our exploration of inflatables to Baymax the inflated robot from the Disney movie Big Hero 6. She showed *solidarity* in helping the other participants at her table. For the project, P9 was eager to integrate as much of her knowledge as she could, and she was keen to build something different from everybody else. She had a specific *intentional* vision in her first sketch of the brainstorming activity (in the morning of the second day), which she pursued more or less unchanged. For example, she chose materials in very similar colors to her initial sketch (included in her final poster, Figure 4), which was drawn without knowing what fabric we would supply.

She ran into several difficulties with the project, mainly based on her ambitious scope given the time limitations. She proposed an octopus hat with eight curling tentacles, which she scaled down to two tentacles as a prototype. However, after producing these, she discovered that, because she was attempting to *innovate* by making them much larger than the actuators we had made up to that point, they required a larger volume of air to inflate than the simple hand-operated syringe inflation method we were using. She pivoted to using the optional microcontroller air pump setup but the tentacles were large enough to be very difficult to check for leaks. Time constraints ultimately prevented her from completing a working prototype, but she articulated the challenges well and had ideas for future solutions.

Like many of our participants, P9 had wide-ranging interests (e.g. “the immune system, outer space, and various random interesting facts”). When asked if she might make pneumatic airbag actuators in the future, she replied that she “may do it because I feel like it is a very interesting idea and a process,” – though she may have said this out of politeness – “but I may not do it because there are many other things that I also find interesting.”

When asked how the pneumatic curling actuators could be used, she suggested "maybe in biomedical engineering for, for prosthetics, or moving joints," which aligns with her stated possible career path of “bioengineering (immunoengineering).” However, she was overall skeptical that the workshop content would be relevant to her studies or future career, with a "3" in response to this question on the post-survey. (Her sister, P8, flat-out denied it would be useful, stating that "I'm planning on doing nursing, so I don't think it would.")

However, the lack of future applicability didn't appear to be a negative for her; P9 appeared to enjoy simply building something new (albeit frustrated by the limited time), and she even asked if she might be able to come back in the future. She was confident in her understanding of the engineering challenges that would need to be solved to make the project work.

In our observations, P9 seemed highly motivated by the thrill of the chase for knowledge, and she enjoyed learning something cool and impressive. In other words, P9 was most aligned with **research as a way of obtaining and proving knowledge**.

6 RESEARCH AS A TEMPLATE FOR EDUCATIONAL ACTIVITIES

We offer this documentation of our workshop as an example of how cutting-edge research, which might otherwise be the exclusive domain of a small set of graduate and advanced researchers, can serve as a *template* for fun, educational, and ideally meaningful active experiences for a much wider variety of participants. We see our own “ways of working” in a research context as substantially distinct from both disciplinary course-based learning and most hybridized “STE[A]M” education (as described in subsection 6.2).

From the other side of the table, we note that the activity of distilling our research practices into a lesson plan was an effective way to reflect on our own processes, values, and skills. Articulating these has many potential benefits for the lab, including: identifying gaps between current and potential workflows; serving as a conceptual “quick-start kit” for future research; and making it easier to onboard new members. While it was not the immediate goal of this work, our analysis of our participants trajectories and aspirations has also influenced the way *we* carry out research processes, and what research means to ourselves and our collaborators in the lab–perhaps this is “Education as a Template for Research.”

As such, we hope this example can be instructive for two audiences: 1) educators who might invite researchers into their classroom, and 2) the researchers who might be invited. We discuss our outcomes of relevance to educators in subsections 6.1 and 6.2, and we offer our synthesized guidelines for researchers in subsection 6.3.

6.1 Roles for research in student development

Instead of choosing just one sub-process to focus on, we designed a multi-activity plan touching, at least briefly, on each mode of the whole morphing matter research process. While this approach had drawbacks – “not enough time!” was a frequent piece of feedback from the participants – the somewhat chaotic and multivalent atmosphere of the workshop was both authentic to our own methods and made space for participants to engage with aspects of the process that were relevant to their own interests and aspirations. We chose teenagers as our participants because they are capable of complex and self-guided work and are at a crucial moment with respect to their future aspirations and goals.

Figure 7: P9 working on the Inflatable Octo-Hat. Left: P9 used rigid construction techniques as the basis of her hat. She plotted the circles and rectangles onto cardboard using string and her knowledge of geometry, and assembled them with hot glue. Center and right: she found sparkly and neon-bright fabrics to make her hat larger-than-life.

In the workshop itself, we did not have any higher-level conversations about the nature of research or how it is practiced in human-computer interaction, nor did we present specific morphing matter research other than the immediately relevant Aeromorph paper. Nonetheless, as discussed in subsection 5.2, participants did encounter various facets of research, as we experience it, in their own ways – as a collaborative building process, as a set of methodologies, and as a path for acquiring knowledge. These participant trajectories point to various roles that research activities could play in education over a longer timeframe. For example, P4 might be encouraged to articulate exactly what methodologies she was tacitly applying to her project to clarify how her existing knowledge relates to her future aspirations. P9 might similarly be encouraged to take a principled look at how her varied knowledge fits into higher taxonomies, sparking novel connections for her which could feed cyclically into new paths of learning.

6.2 Cross-disciplinarity

A *discipline* is "a branch of learning or knowledge; a field of study or expertise" [59]. Any discipline has practices that have been honed into conceptual toolkits for its practitioners bring to bear on complex problems, including methods for conducting inquiry and values for assessing results. For example, the Scientific Method is a framework for rigorously constructing new scientific knowledge; scientific practice is ideally precise in its aims and reproducably accurate in its data and conclusions. Design methods like sketching, contextual inquiry, and critique are scaffolds for developing specific proposals and formalizing reflection. Design practice is ideally multivalent, context specific, and responsive to complex problems.

Our three core research processes often (though not always) align to three primary disciplinary areas:

- **Constructing** typically requires *Engineering* approaches: we use modified or novel fabrication devices (such as the CNC dough stamper in Figure 2) and choose appropriate cutting, attaching, molding, and patterning methods for particular materials at particular scales; we *evaluate* these on the basis of viability, repeatability, and efficiency of time, materials, or other production costs.
- **Characterizing** draws on *[Materials] Science*: we form specific hypotheses about material properties, often including a computational model of morphing responses, and gather empirical data to refine and validate these hypotheses; we *evaluate* these on their accuracy and robustness as either predictive or generative models, the appropriateness of the type of model chosen (e.g. statistical vs purely geometric), and their applicability to similar materials.
- **Integrating** involves *Design* methods like sketching, futuring [45], interface design, and deploying prototypes (such as the participatory workshop from Ku et al [46] in Figure 2). We *evaluate* our results qualitatively and critically, on criteria including contextual appropriateness, human experience, and composition.

In progressing through the processes, morphing matter research can be summarized as a shifting interplay between three archetypal disciplines, serially drawing on deep procedural knowledge to solve problems that may be intractable otherwise. We believe that approaches like this are necessary to solve the complex problems at the frontier of contemporary research.

However, we observe that shifting disciplinary foci are atypical in current K-12 education. STE[A]M approaches overlap to some extent with ours. However, STEAM is typically implemented in one of two modes. In the first, described in Mejias et al [53], disciplines are typically "unidirectionally instrumentalized": one discipline is used as a frame or a prop for the other; for example, students may be encouraged to draw pictures on a microcontroller project, allowing the activity to claim a veneer of "art" over what is more fundamentally a programming lesson. Indeed, the specific meaning of "art" is often vague, and may refer to superficial aesthetics or simply any element of learner creativity [14] (an attitude trivializing both Art and STEM practices). Design as a discipline might be conflated with Art, considered only in the context of Engineering Design [19], or ignored entirely. In the second mode, described by Bevan et al [4], the disciplines are *hybridized*: the intersection of "STEM" and "Art" gives rise to a new, third discipline with its own methods and values. These methods may not fully represent the component disciplines–for example, the skills needed to successfully complete an e-textiles project, while valuable in their own right, do not necessarily translate to success with either electronics or textiles taken individually [40]–and Bevan points out that the arts practices in particular are often under-represented in the hybrid. Additionally, it may be difficult for students to understand how a specific, hybridized STEAM project relates to their other learning or their own interests, even if its component practices would.

We see morphing matter research as a key exemplar for how cross-disciplinarity can be practiced, not as an *unbalanced* or *blended* practice, but as one in which the disciplines are *interleaved*. By giving serious consideration to each base discipline, deeper insights and connections can be achieved. For example, we specifically set aside times for context-based brainstorming, peer critique, and developing presentation skills; these key Design methods are not frequently described in STEAM teaching reports. While it would be premature to make specific claims about learning outcomes, given our small participant pool, we observe that student self-reports did use language from all of design (e.g. P3 discussing fabric choices for aesthetic effect, Team Puff Muscle situating their project in a very specific scenario), science (P4's sealing pattern experiments), and engineering (P9's discussion of a single actuator as a prototype). Topic shifts (e.g. when we wrapped up the Characterizing activity and began the discussion of fashion design as a context) additionally provided opportunities to re-invigorate the room's energy levels and re-integrate participants who were less engaged.)

6.2.1 Cross-disciplinarity allows low prerequisites. Any lesson plan ideally has prerequisites matched to the target participant group. One approach to ensuring this is to build directly on the participant's known curricular learning, such as in traditional "enrichment" activities which flow from specific lesson content. While we did check our lesson plan against the curricular expectations for our participants (in subsection 4.3), we also note that our research domain is particularly flexible in this regard. Morphing matter findings often involve *combining* insights across disciplines, making it possible to introduce morphing matter topics with only basic knowledge in a particular component discipline. In our lab, it is frequently the case that researchers use their deep knowledge of material engineering to learn more about design contexts, or vice versa. Similarly, because there's no single specific kind of knowledge required to do morphing matter research, it is possible for any of the processes to be scaffolded without losing authenticity to the overall arc of research. For example, the original Aeromorph paper includes a fairly sophisticated computational model of bending in constrained airbags, but that paper's figure 8, relating the width of the sealed diamond area to the bending angle of the actuator, is a real and serious contribution of the paper, and it can be replicated with basic measuring and charting skills.

Cross-disciplinarity and a focus on combination can also level the playing field without forcing participants to ignore the skills they do have. In our workshop, several participants had existing sewing skills and we didn't discourage from-scratch sewing in the final project, but we also supported modifying thrifted garments and using non-sewing attachments like safety pins and tape. This re-emphasized the *combination* of actuator and garment.

This robustness to scaffolding is similar to the concept of "low floors" from maker education research [69]. However, we wish to emphasize that we are specifically referring to multiple possible conceptual entry points, not that any of them are necessarily "easy." Extending the architectural "floors and ceilings" analogy, this might be summarized as "doors facing many directions."

However, we see cross-disciplinarity as more interesting approach to minimizing prerequisites, as widely cross-disciplinary domains can be scaffolded quite radically without diluting their essential nature. For example, games studies and accessibility both require deep cross-disciplinary collaboration.

6.2.2 Practitioners as Collaborators in Cross-disciplinary Education. One difficulty with teaching cross-disciplinary topics is that it can require specific and unique expertise. In arts education, practicing artists can have important roles both as collaborators with instructors [20] and as fully hybrid teaching artists [7]. Arts practitioners may be able to stay engaged in the construction of new knowledge in a way that is inaccessible to full-time instructors, and they can shape invitingly different educational dynamics [29]. However, cross-disciplinary practitioners are much more rarely found in K-12 classrooms.

6.3 Expanding to Other Template Domains

We believe that morphing matter, with its deep blend of engineering, science, and design, is a particularly apt research domain to use as a template for cross-disciplinary education. However, we do not think that morphing matter is the *only* such domain. Because we have found that collaborating on the design of educational workshops can be highly worthwhile – it can help researchers reflect on their own processes (potentially leading to new lines of inquiry), it can improve public discourse about a topic area, and of course it might inspire the next generation of colleagues – we hope that this work inspires other researchers in other domains as well. In this section, we offer guidelines based on our experiences for such researchers.

6.3.1 Identifying Potential Domains. To enable the advantages of cross-disciplinarity as discussed in subsection 6.2, template domains should ideally involve several distinct ways of working and evaluating the work. Many such domains will involve a hybrid between a science or engineering discipline and a design, humanities, or arts discipline; for example: computational linguistics, information visualization, data journalism, human-robot interaction, and procedural art. However, research combining engineering with a science discipline, or a humanities and an arts discipline, may also be a compelling template. For example, metamaterial structures which combine mechanical engineering and computational calculation [38], or using hairdressing as a way to assess archaeological records [75].

6.3.2 Lesson-Planning Process. After the important preliminary step of teaming up with knowledgeable educators, our overall process can be summarized as:

(1) Gathering exemplary research in our area, including our own past work as well as research from similar labs and frequent citations.
(2) Analyzing this body of work for recurring processes, priorities, and methods of evaluation, and refining this analysis in discussion with leading members of the lab.

(3) Choosing an existing replicable research finding in our domain. (In this work, we chose the diamond airbag actuators from Ou et al. [57].)
(4) Choosing a framing context with relevance to the student participants. (In this work, we chose fashion.)
(5) Selecting processes from the exemplar research that are most relevant to the key methods of our lab, thereby refining our definition of the key methods of our lab.
(6) Designing scaffolded versions of the selected processes to make them accessible to our participants within our time constraints. For example, for "constructing," we prototyped a way to make the airbags with a simple linear heat-sealer and a hot-glue gun. For "characterizing," we lead a discussion to quickly narrow down a particular parameter to measure.
(7) Assessing the scaffolded activities for what skills would be required and honed, then aligning the skills to education standards for our participants' age range in our geographic area to check that the skills are appropriate and relevant.

The first two of these steps may feel unnecessary to other labs; nevertheless, shifts in research priorities and methods can occur over time, and we found the process valuable. The final step will likely be the most unfamiliar to laboratory researchers; we provide a worked-through example in subsection 4.3, but the specifics will vary with geographic region and participant demographics – collaborating with expert educators will be key. For the rest of this section, we offer tips on steps 4-6.

6.3.3 *Choosing a research finding and context: supporting novelty.*

In shaping a lesson plan to spark participant interest in cross-disciplinary research, we encourage researchers to consider a project in which the path to novelty is reasonably expedient. Particularly in the sciences, "student work" often involves replicating known results, unlike "real" research. While we based the overall trajectory of the workshop on a known type of actuator, it was important to us that the participants could ultimately make their own novel contributions. We avoided discussing the Aeromorph paper until after the initial constructing and characterizing activities, and we encouraged exploration of airbag types and features that were not the ones documented in that work. Most importantly, we centered specificity as a desirable quality in our project brainstorming activity: who is this for, and when? How can the engineering choices support the unique design concept? More broadly, we chose fashion design as a framing aspect of the workshop because fashion can be highly relevant and personal – it is likely that many people have something unique to "say" with fashion.

Similarly to how cross-disciplinarity offers many points of entrance to learning (subsubsection 6.2.1), we found that it also makes it easier for participants to find novelty in some area or another. For us, morphing matter's explicit inclusion of "integration" as a core process directly supports contextuality and therefore uniqueness. Other domains might be applied to the students' own contexts in ways that differ from the existing research, such as a molecular gastronomy [2] investigation of local or cultural foods, or might be rapidly evolving with lots of "low-hanging fruit," such as generative art.

6.3.4 *Accessibility in a classroom setting.*

STE[A]M educators often grapple with tight classroom budgets, time constraints, and questions of scaling [18]. Researchers also often value accessibility and the broader impacts of their work. Especially within work written for HCI audiences, "democratic" morphing matter research frequently centers tools and materials which are inexpensive, safe, and easy to use [22, 84]. However, in practice, HCI research often posits "future" systems and abstracts away any expertise needed to set up or maintain a system. For the benefit of HCI fabrication and morphing matter researchers, we wish to summarize practical aspects of "accessibility" in an education setting, with reference to our own experience.

For this workshop, we chose heat-sealed plastic as our fabrication technology because it is reasonably easy to master and the materials are inexpensive; we hoped these qualities could encourage students to explore broadly without being too precious. However, even "inexpensive" is a barrier relative to "already owned," especially for youths. Projects that can be accomplished in students' homes could allow them to continue exploring after the workshop [11], and may inspire them to look for other morphing phenomena in their everyday environments. For example, P7 said she could see herself using the skills from this workshop toward a Halloween costume, because "we have a pump at home I can use." Heat sealers are not particularly expensive (prices vary, but we paid approximately $40 USD per sealer) but they're also not widely owned in homes or supplied in schools; when we asked participants if they might "do this again sometime," being deliberately vague about what "this" might include, several participants mentioned specifically that they don't have a heat sealer so they are unlikely to do so. (P1 and P7 had both used a heat sealer before, but not frequently and not with high confidence.)

To support students' ability to experiment with learned techniques on their own time, activities should be not just inexpensive and safe, but ideally also doable with common household or public materials. Of course, there's very little that can be guaranteed to be found in *any* student's environment, but local nature materials, or items which can be supplied to students to take with them, are a start. Within morphing matter, that might include cooking technologies or studies of biomechanisms in local nature. Other domains could support nondestructive or observational research, such as digital humanities with free and open-source corpora, or social sciences where *other people* are the locus of study.

7 LIMITATIONS AND FUTURE WORK

We've presented our own experience of using our "real-world" laboratory practice as a template. This is in several ways a pilot work. First, our workshop is based on *our* definition of "morphing matter research." That definition incorporates work from a range of other labs and neighboring disciplinary foci, but it is ultimately biased by our own research strengths and interests. In documenting this work the way we have, we dearly hope that the landscape of educational workshops is enriched by cross-disciplinary researcher perspectives outside our own. Second, our workshop itself was time-constrained, especially in the amount of time we had to collect directed participant feedback, and in the number of participants. Nonetheless, we believe these preliminary results are encouraging for future workshops either with more participants in collaboration with learning analytics researchers, or derived from different topic areas in collaboration with other labs. Lastly, we have focused on the perspective of the laboratory team in this paper, but our workshop series is a collaborative effort between the Morphing Matter Lab and an educator with Brilliant Labs, and our overall project includes liaising with classroom and community educators. Future research could study the educator side of engaging with cross-disciplinary practitioners, and best practices for productive collaboration, as has been done in arts contexts [20].

8 CONCLUSION

In this paper, we reflect on the process of using morphing matter research as a template to design and carry out a pilot workshop for teens. The bounds of "research" – who participates in it, how it is carried out and evaluated, and to what purposes – are somewhat amorphous, varying widely by context and discipline. Even within our own lab, identifying "how we work" was non-obvious. Nonetheless, within a particular research domain, recurring research processes can be identified. Understanding the processes makes it possible to analyze the underlying skills, design relevant activities, and present an interactive arc of research inquiry that is guided while remaining essentially authentic. When we carried out this process, we found that our teenage participants had salient experiences relevant to curricular standards that are most closely associated with our core research processes, and that different participant trajectories through our workshop reflected different ways of looking at research itself.

We believe that morphing matter research is particularly suited to being used as a template in this way, being deeply cross-disciplinary and having relatively low barriers to entry in either equipment or pre-requisite knowledge. However, we hope that our example can inspire researchers in other domains to distill and scaffold their methods for outside audiences as well – they might inspire, and teach, and possibly learn about their own research in the process.

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