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Fabrication of a physical circuitry activity booklet for English instruction

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Abstract

This case study examines an approach to designing and fabricating a technology-based medium for use in a non-science, technology, engineering, and mathematics (STEM) subject. The booklet, titled *Rock, Paper, Physics!*, was used as a medium for instruction on simile, metaphor, and personification to an 11th-grade honors English class by deploying and manipulating visible circuitry and hot-swappable circuit elements. We explored multiple fabrication approaches, including conductive two-dimensional printer ink, three-dimensional-printed materials, inlaid wires with matching cut-out troughs, and more, before settling on magnets and copper tape for reliability and ease of assembly. We report on the collaborative, iterative process that informed the final booklet design, the partnered English teacher's perspectives on ease of use, and the potential of this approach to impact students' attitudes about STEM subjects in a non-STEM course.

Keywords: Fabrication; Circuits; STEAM; STEM; English; Physics; Physics education research; Integrative STEM

1. Introduction

In the early 2000s, education policy and accountability pressures often emphasized science, technology, engineering, and mathematics (STEM) over the arts and humanities.[1] Since then, some educators and researchers have advocated for the reintegration of the arts and humanities into these STEM classrooms, often calling it "STEAM".[2] STEAM links STEM with the arts, with a common approach being the use of arts, such as music, color, photography, or other creative endeavors, to foster students' interests in STEM. STEAM activities and classrooms have been shown to increase student adaptability, foster creative approaches to complex problems, strengthen perseverance when faced with challenging concepts, and promote the development of transferable skills.[3]

In 2012, Sanders[4] described "Integrative STEM" as an educational "best practice model".[4](p.2) In this work, he defines integrative STEM education as:

> technological/engineering design-based learning approaches that intentionally integrate the concepts and practices of science and/or mathematics education with the concepts and practices of technology and engineering education. Integrative STEM education may be

> enhanced through further integration with other school subjects, such as language arts, social studies, art, etc.[4](p.2)

This work focuses on the latter portion, "enhanced through further integration" of Sanders' definition by using circuitry, an engineering and physics concept, to support figurative language instruction in a high school English classroom. This is achieved through the development and collaborative design of an interactive activity booklet titled *Rock, Paper, Physics!*. Here, scientific concepts serve a non-STEM learning goal: English instruction. This reverses a common STEAM approach in which the arts are used primarily as an entry point into STEM. By making English the focus rather than science, we are integrating STEM and English. This highlights their intersection and mutually supports the learning of subjects historically taught independently.

This work focuses on answering four main research questions surrounding the iterative and collaborative design processes:

(i) How does the teacher co-design process affect the creation and application of this STEM medium for teaching English concepts?
(ii) What teacher-facing support is necessary for independent implementation?
(iii) How do different fabrication choices trade off reliability, cost, and "hot-swappability" when building paper-based circuitry elements for classroom use?
(iv) What are the impacts on learners' engagement and their attitudes toward STEM?

In answering these research questions, this study contributes to the field by documenting the fabrication history and methods used to create the interactive booklet and describing the iterative, collaborative design process with an 11th-grade English teacher that shaped the final activities.

The rest of this article is organized as follows: Section 2 presents background research on the history of STEM and STEAM, as well as on various fabrication methods and technologies related to paper fabrication. Section 3 covers all materials and methods used in this work. Section 4 reports the development process of the activity booklet and the various fabrication processes attempted. Section 5 discusses the final design of the booklet and the discussions with the English teacher. Section 6 highlights the collaborative design process with the English teacher, and Section 7 presents the conclusion of this work.

2. Background

STEAM is a movement in response to STEM that highlights the usefulness, necessity, and interconnectedness between the arts and traditional STEM disciplines. An example of a STEAM program is *Quavers to Quadratics*[5], which incorporates music and art into the exploration of physics, making the two inseparable. In addition to simply being fun[5], STEAM-style coursework and lessons have been shown to engage more students in traditional STEM fields[6], promote creative thinking[7], and improve non-STEM students' art practice and knowledge.[8] *Quavers to Quadratics* teaches Physics in a non-formal after-school program setting.

STEAM and early integrative STEM differ in their instructional focus. Initially, integrative STEM research focused on bringing hands-on STEM activities into STEM classrooms. Some examples of integrative STEM programs include the National Energy Education Development[9] and KidWind.[10] The National Energy Education Development provides classroom activities that support circuit instruction, whereas KidWind offers similar activities often used in non-formal settings, such as field trips.

More recent integrative STEM studies have brought STEM subjects into non-STEM classes using a method very similar to that of this research. In Spain, researchers distributed STEM activities in two fourth-grade elementary school courses.[11] They concluded that students developed more favorable attitudes and beliefs toward science after the activity. Our present research aims to expand the findings of similar works by targeting an older audience in more specialized courses.

As additive manufacturing has become more popular and milling technologies have become more accessible, the makerspace DIY movement has exploded. Makerspaces have expanded rapidly in the United States, serving a wide range of participants and skill levels.[12] Rogers and Portsmore[13] sought to bring this makerspace movement into elementary and middle school classrooms as an early introduction to engineering.

Rather than asking 10-year-olds to work with lathes and mills, Rogers and Portsmore[13] used ROBOLAB software and LEGO kits in a play space to foster learning and excitement. Students were able to build small, simple robots, program them, and watch them function in the real world. Their research specifically focused on women and underrepresented minorities within STEM to help them develop positive associations with engineering before stereotype threat and other negative sociopsychological factors came into play. He found that "LEGO-based engineering design projects, when presented in the proper context, can provide hands-on opportunities for girls at a very young age, thus helping to build and develop their confidence and interest in math, science, and engineering".[13](p.9) One key component of the study was that the environments created by ROBOLAB and LEGOs were interactive. Roschelle[14] analyzed a variety of studies surrounding non-formal interactive learning environments and found that interactive environments sustained engagement longer than traditional lessons. Interactive environments allow students to use their imagination while learning, making the experience more pleasant and impactful.

In a separate study, Vanparys *et al.*[15] implemented an interactive book reading. While not exactly like a booklet, interactive book reading involves group sessions in which students engage with the text under their teachers' guidance. Teachers pose questions while students read aloud; students discuss specific sentences and paragraphs in groups; and meaningful connections are drawn between the book's content and the real world. Researchers found "significant positive effects... on first graders' expressive target vocabulary"[15](p.1) when interactive book reading sessions were used.

Another recent study informing the present work focused on the use of generative artificial intelligence to replicate essential human practices.[16] The present work builds on some of the principles of this study, emphasizing the essential role of human inquiry and discovery. While technologies can facilitate some aspects, they are not designed to replace these foundational learning objectives or practices.

The booklet developed in this study uses the concepts of metaphoric mapping instruction (MMI) to teach students similes and metaphors.[17] MMI is a teaching approach in which learners are taught to understand figurative expressions by mapping structured correspondences from a familiar or physical concept to a more abstract concept. By using physical, familiar concepts, MMI incorporates embodied cognition[18] and multimodal learning.[19] Recent studies have shown that teaching figurative language through MMI has increased learning retention and student engagement.[17]

Regarding the technical design of the activity booklet, we drew on prior efforts in circuit-construction tools.[20]

Researchers and makerspace enthusiasts have also experimented with methods for adding low-profile circuitry to flexible materials. Conductive two-dimensional printer ink is a novel approach, but it is expensive and generally unreliable, depending on the printer type.[21] Conductive three-dimensional (3D) printer filament is more reliable, but most teachers do not have easy access to a 3D printer and conductive filament.[22] Copper tape is affordable, accessible, and offers a familiar medium for both students and teachers.[23]

Methodologically, the present work draws from design-based research (DBR)[24,25], an approach in which researchers and practitioners collaboratively design and iteratively refine education interventions in authentic learning contexts. DBR uses empirical evidence from each iteration to improve both the intervention and the theory that explains how and why it works. Rather than isolating variables in highly controlled settings, DBR emphasizes cycles of design, enactment, analysis, and redesign, and treats classroom constraints, stakeholder needs, and implementation realities as central to the research process.

3. Materials and methods

The DBR approach was enacted through rapid prototyping of paper-based circuitry artifacts and collaborative co-design with classroom teachers. Across successive iterations, we refined both the fabrication method and the instructional design of the activity booklet. Iterations were evaluated through short-cycle user testing and teacher interviews, with design changes guided by observed failure modes, usability barriers, and teacher feedback.

The primary design requirements for the booklets were: (i) affordable for teachers' budgets, (ii) rapidly assembled without specialized equipment, (iii) reliable under repeated student handling, (iv) visually legible for students with no science experience, (v) modular with hot-swappable circuit elements, and (vi) usable by teachers without formal training in electronics.

3.1. Setting and participants

Testing and co-design occurred in three contexts throughout this work: early usability interviews, use in an after-school program, and classroom co-design and deployment. Each context had its own protocol, participants, and data collection methods.

3.1.1. Early usability interviews

Prototype leaflets and booklets were tested through informal user interviews with graduate students (n = 13) affiliated with the Physics Education Research group and the ATLAS Institute at the University of Colorado Boulder. Each user was given the leaflet separately and worked through the leaflet with the researcher present. Each user took approximately three to ten minutes to complete the activity.

These interviews were used to identify usability problems, such as connection instability, unclear instructions, orientation errors, and more. These tests were also used to compare how users with different technical backgrounds approached open-ended circuitry tasks. The activities described in Sections 4.1 and 4.2 were distributed within this context.

3.1.2. Non-formal learning deployment

A high-variability booklet iteration was implemented as a supplemental activity in an after-school science program serving elementary-aged youth (n = 22). This deployment was used to evaluate how younger learners approached open-ended circuitry exploration, how much scaffolding was required, and what types of engagement the medium supported. The activity described in Section 4.3 was distributed within this context.

3.1.3. Classroom co-design and deployment

Two English teachers participated in interviews and iterative feedback cycles. One high school teacher ("Candice," pseudonym) participated in five booklet iterations, with interviews approximately two weeks apart, and implemented the finalized booklet activities in her 11th-grade honors English course. A middle school teacher ("Linda," pseudonym) participated in two interviews intended to assess the usability and feasibility across grade levels and identify teacher-facing barriers to independent implementation. The first interview for both teachers followed the protocol outlined in Supplementary File S1.

During interviews, participants (teachers) were given about 20 min to explore the booklet shown in Figure 1. They were encouraged to ask questions and, within a few minutes, produced a working circuit. Some combinations required prompting to elicit interesting interactions (e.g., placing a capacitor in series with a light-emitting diode [LED], allowing it to charge until the LED was very dim, then flipping the capacitor to observe a bright flash). After exploration, we discussed curricular integration, including timing, lesson planning, anticipated student engagement, and additional implementation ideas.

Candice's 11th-grade honors English classroom consisted of 24 students, with an even 50% split between male and female students. The class was 90 min long, and the booklet distribution took place three months into their school year. The activity and interviews described in Section 5 were distributed within these contexts.

3.2. Booklet and materials

The final booklet was an interactive activity booklet titled *Rock, Paper, Physics!*, which featured visible paper circuits and detachable, hot-swappable circuit elements. Across iterations, fabrication approaches included conductive ink printing, 3D-printed conductive components, inlaid wire channels, and copper tape circuitry. The final construction used copper tape for conductive traces and neodymium magnets at circuit junctions to create durable, repeatable electrical connections and support rapid component swapping.

Circuit elements used across iterations included batteries, LEDs, resistors, capacitors, switches/buttons, and removable wires. Teacher-facing support included a short construction guide and a troubleshooting/FAQ guide that addressed common issues observed during user testing.

3.3. Iteration workflow and decision criteria

Each iteration followed a common design cycle:

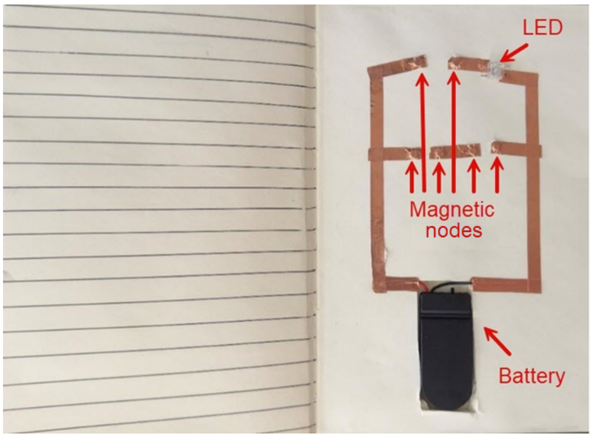

Figure 1. The version of the booklet that was originally given to the teachers for testing
Abbreviation: LED: Light-emitting diode.

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(i) Build: Fabricate a prototype leaflet or booklet activity using a candidate connection strategy and a set of circuit elements.
(ii) Test: Observe users interacting with the prototype with minimal prompting; collect feedback on ease-of-use, engagement, and failure points.
(iii) Diagnose: Document failure modes.
(iv) Revise: Modify materials, junction design, node count, instructions, and activity structure.
(v) Re-test: Confirm whether revisions improved stability, reduced troubleshooting burden, and supported the intended learning activity.

Design choices were then made by comparing prototypes against the study requirements (as outlined in the introduction to Section 3), with particular emphasis on connection reliability under repeated handling, reduced manufacturing time for teachers, and improved student autonomy during activities.

3.4. Data sources and measures

Data sources were selected to capture both design usability and classroom feasibility. Research observations and field notes were taken during user testing and classroom use to document observables, such as the time taken for students to get their first working circuits. Researchers also observed the frequency and type of troubleshooting events, evidence of student engagement, and collaborative behaviors.

Teacher interviews focused on the teachers' perceived usability of the booklet. They also revealed how the booklet aligned with their curricular goals, helped anticipate student challenges and classroom management considerations, helped develop scaffolding and teacher-facing support systems, and, over time, revealed the teachers' confidence in independent implementation.

Audio/visual (A/V) data were taken during all interviews and classroom distributions to corroborate research observations, field notes, and teacher interviews.

Pre- and post-activity surveys were distributed only to students in the 11th-grade English class. A "Lab Note" post-activity worksheet was given only to elementary school students in the non-formal after-school program. Teacher-distributed end-of-semester questionnaires were also distributed to students in the 11th-grade English class.

3.5. Analysis approach

Qualitative data, including A/V data, researcher field notes and observations, and teacher interviews, were analyzed using an iterative thematic process. First, researchers generated initial codes aligning with project goals. Codes were then refined across iterations as new failure modes and design considerations emerged. The refined codes showed different user states: "play," "getting 'results,'" "discussing with educator," and "writing." "Play" was recorded when users were actively engaging with the booklet without aid from either the researcher, teacher, or the University Educator (UE), depending on the recording context. "Getting 'results'" was recorded when users were actively able to get an LED to light up. "Discussing with educator" was recorded whenever users discussed the booklet with the researcher, teacher, or UE, depending on the recording context. "Writing" was recorded when users were writing their "Lab Notes," answering posed questions, or creating a new activity in the booklet, depending on the recording context. Each half-minute of the session was coded, and the number of educators and students, along with their genders, was recorded. Findings are reported as a design history of fabrication decisions and an account of how teacher feedback shaped activity structure and teacher-facing supports.

A Wilcoxon signed-rank statistical analysis test[26] was performed on quantitative results from the pre-/post-activity surveys using a Jupyter Notebook environment running Python (version 3.14.2) by importing SciPy module. Additionally, these results were summarized descriptively and used to contextualize qualitative findings. Physics and English education were not the primary focus of this work, but some preliminary results surrounding student attitude shifts toward Physics are included.

3.6. Ethics and consent

This study was approved by the CU Boulder IRB under record number 24-0037. All data collection procedures followed applicable guidelines. Adult participants provided informed consent. Youth-facing deployments acquired both parental consent and child assent.

4. Booklet prototyping

The technologies and practices discussed in Section 2 are often implemented in non-formal learning settings, such as after-school programs.[5–7] They rely on voluntary participation by students, which can introduce selection bias among those who use these creative learning tools.[5–8] They are also often costly and require intervention from a highly specialized third party, such as a graduate student, professor, or engineer.[12–16,21] These issues compound, making it unlikely that the average teacher, classroom, or student in the United States will experience fun and novel teaching technologies and practices relating to STEAM.

This study outlines the design iteration and fabrication processes used to create a physics-based activity booklet designed to teach English subjects to middle and high school students. The goal of this booklet is to bring some of the technologies and practices highlighted in Section 2 to more students in a formal learning setting, building on the affordances of informal education to encourage play and identity.

4.1. Light and color leaflet

The first attempted rapid prototype for this booklet utilized polarizing light filters, a button, and LEDs (Figure 2). A circuit was created on the inside of a folded sheet of paper. Copper tape was used to connect the circuit elements. This configuration contained a resistor, multiple static LEDs, and one rotatable LED. This design illustrated the directionality of LEDs and enabled students to engage in creative problem-solving as they had to discern a circuit diagram from the behavior of circuit elements as the LED rotated. A similar method was attempted using color filters with color images.

Students became frustrated with the "black-box approach" (hidden circuitry) and the inability to see the circuitry. Originally, this design was intended to be torn apart so students could view the circuitry after puzzling it out, but in practice, students were either too timid to tear the leaflet apart or unable to do so due to the limited supply.

Another reason these leaflet designs were archived was their overwhelming focus on Physics. Rather than being used to teach a non-science subject such as English, these activities were pure Physics lessons on light polarization and circuitry. Thus, these failed to target the ideal audience and bring STEM subjects into non-STEM classrooms. These shortcomings enabled the first redesign, which focused on bringing similar physics concepts into a humanities classroom using a puzzle-like structure.

4.2. Puzzle leaflet

After deciding to remove polarizing filters and color filters from the booklet design, we began focusing on the circuitry and different ways to utilize it in non-science classrooms. One of these involved a date-association puzzle in which students were tasked with matching the events in an image to the dates they occurred (Figure 3). This was originally conceived as an activity for a middle school global history course. Each image had copper tape on the back that attached to matching copper tape on the leaflet, completing the circuit with the corresponding LED only.

In these models, the leaflet became increasingly unstable due to the natural oils on students' fingers. The copper tape would not stick and, even when pressed tightly to the underlying circuitry, would cause the LED to flicker intermittently. These design challenges led to the addition of small neodymium magnets beneath each connection point, or junction, to secure a stable electrical connection.

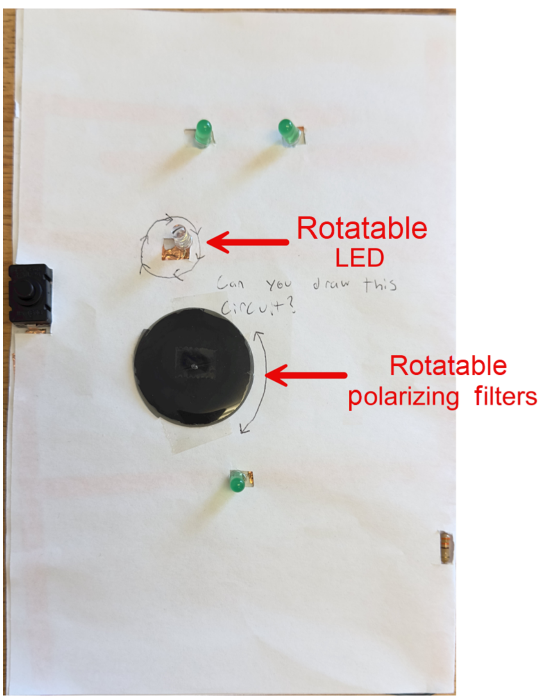


Figure 2. A leaflet with a circuit hidden beneath the page. The circuit diagram is hidden beneath two polarizing filters aligned perpendicularly. These filters are connected by a rivet, allowing the top filter to rotate. There is also a loosely connected light-emitting diode (LED) that can be rotated. In the proper configuration, the top two static green LEDs and the white rotating LED illuminate. Otherwise, only the bottom static LED illuminates.

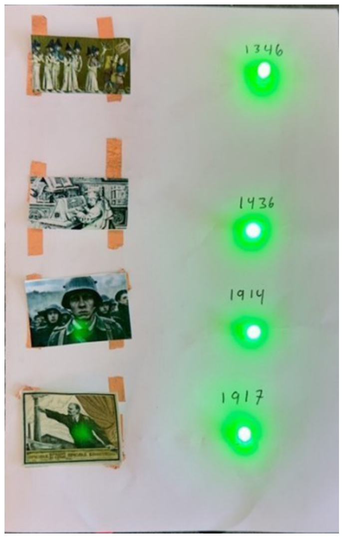


Figure 3. A leaflet with a puzzle design. Each image has a different configuration of copper tape on the back, which completes the circuit and turns on the light-emitting diode only when the event in the image matches the correct date.

During user testing, students enjoyed the leaflet's puzzle aspect but did not appreciate its rigidity and reliance on memorization. This early design also lacked the freedom to experiment with circuit elements, as it was simply a matter of placing an image in a spot.

This leaflet was given to two groups of graduate students: those enrolled in a Creative Technologies and Design engineering program and those enrolled in Physics. The Creative Technologies and Design students enjoyed the puzzle aspect the most, while the Physics students enjoyed the hidden circuitry. Neither group had memorized dates associated with the historical events in the photos, and were guessing which photo went with which year. After each group had successfully placed each event on each date, they lost interest in the leaflet because there was no freedom to experiment with it further.

4.3. Maximal variability booklet

The maximal variability booklet design enabled a large number of circuit elements to be connected in series and in parallel. Students were given multiple resistors, wires, capacitors, inductors, and buttons, all of which could be easily affixed to the booklet through the magnets at each junction (Figure 4).

The booklet in Figure 4 was tested within a weekly after-school program for elementary school students (*n* = 22).[27] The booklet served as a "bonus activity" for early elementary students to experiment with after completing three prior, more basic evaluation and management activities.

4.5. Fabrication

This was the first design that required multiple booklets to be rapidly produced. Initial iterations of this booklet included conductive printer ink, physical wires, and conductive 3D filament. Conductive printer ink and 3D printer filament were both too costly to maintain. A vial of conductive printer ink (~$60) was able to print approximately 30 circuitry designs. To utilize conductive 3D filament, a teacher would need access to a 3D printer and purchase conductive filament (~$300). Physical wires were cost-effective but lacked aesthetics and required the teacher to strip the wires for every connection and to cut out a trough in the booklet pages for the wire to rest in, which greatly increased the time to create a single booklet. Eventually, we settled on using copper tape and neodymium magnets to rapidly create secure, modular connections.

In user testing, this fabrication method worked well for both teachers and students. Teachers were able to add designs to the booklet affordably and with relative ease, while students were able to envision the circuits, quickly swap circuit elements, and share their circuit creations with their friends.

4.6. Guidance and complexity

The goal of the Partnerships for Informal Science Education in the Community (PISEC) at this site was to encourage young students to see themselves as scientists. PISEC's primary data sources were A/V recordings of activity tables, weekly "Lab Notes" completed by students, and a pre-/post- semester survey designed to gauge shifts in students' self-perception as scientists. The data is directly related to the *Rock, Paper, Physics!* activity included A/V recordings of students interacting with the booklet and the weekly "Lab Notes."

The "Lab Notes" showed that students were less inclined to write extensively about the activity (presumably because they did not understand the science behind it) but were inclined to relate what they witnessed to their lived experiences (Figure 5). Some students demonstrated some conceptual difficulties with the physics content. However, all students engaged in understanding through embodied cognition and connected observations to lived experiences, suggesting that the booklet was on the right path.

Additionally, students appeared to be engaged in playful exploration. Their interactions with the booklet, peers, and

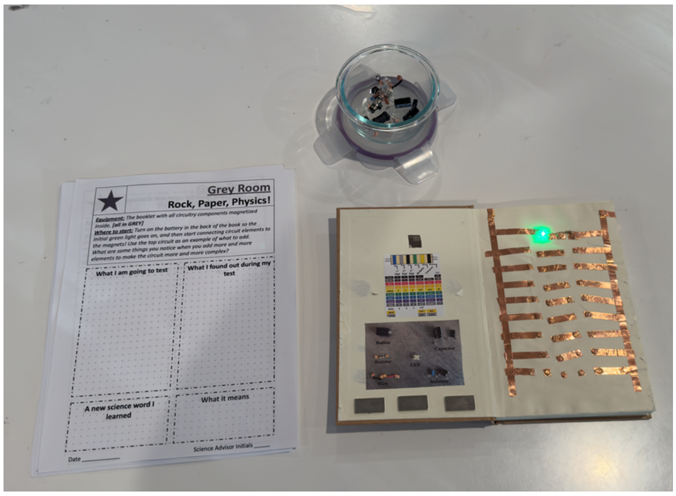
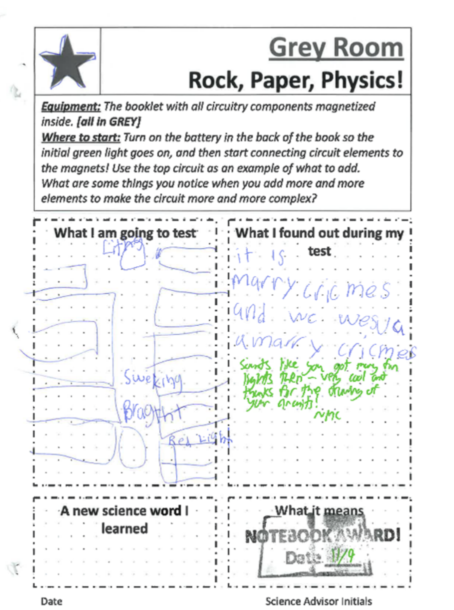


Figure 4. The maximal variability booklet used in the Partnerships for Informal Science Education in the Community (PISEC) user study. A container with circuit elements, a PISEC activity worksheet, and a booklet with circuit labels on the left page and visible circuitry built into the right page. This circuit has a static, hidden battery and a static light-emitting diode. There are 19 possible nodes for additional circuit elements. Beneath each junction is a small neodymium magnet.


Grey Room
Rock, Paper, Physics!

Equipment: *The booklet with all circuitry components magnetized inside.* ***[all in GREY]***
Where to start: *Turn on the battery in the back of the book so the initial green light goes on, and then start connecting circuit elements to the magnets! Use the top circuit as an example of what to add. What are some things you notice when you add more and more elements to make the circuit more and more complex?*

What I am going to test	What I found out during my test

A new science word I learned	What it means
	NOTEBOOK AWARD! Date

Date Science Advisor Initials

Figure 5. One student's "Lab Note" associating the green and red light-emitting diodes in the activity with Christmas. Where the page prompts students to say what they found during their testing, this student wrote "it is merry Christmas, and we wish you a merry Christmas," referencing the carol "We Wish You a Merry Christmas."

student educators (generally an undergraduate student) implied the use of imagination and associations with personal experiences present in "messing about" learning.[28] This is illustrated by a student's association with Christmas: while playing with LEDs, they imagined a Christmas tree lighting up and discussed holiday experiences with friends.

Overall, early elementary students required more scaffolding and structure than this activity provided; it was a mismatched tool for these learners. Students often did not know how to approach the booklet and were unable to create circuits without direct assistance from a student educator. The recordings showed that students enjoyed the activity and were especially engaged when a student educator helped them complete circuits. Students loved being able to place an LED or resistor on the copper tape, feel the magnets engage, and watch LEDs turn on, off, dim, or brighten.

These findings led to a redesign of the booklet to have fewer nodes and fewer circuit element options. Students' need for direction also led to the development of a sequence of increasingly challenging activities to help students grow accustomed to the medium.

5. Results

The focus of this work was on ascertaining the potential use of circuitry to teach in non-science classes. In the booklet's present iteration, students were told to pay attention to how each element behaves when connected with others. Depending on the classroom, students may then be asked to write extended analogies, engage in metaphor exercises, write similes, or personify different circuit elements. Striking a balance among the number of circuit elements, connection nodes, student activities, and overall circuit variability required multiple user studies and teacher interviews. The final design emphasizes moderate variability with guided lessons.

5.1. Hybrid approach with moderate variability with guided lessons

The final iteration of the booklet consists of nine pages of activities, each more complex than the last (see Supplementary File S2 for a wireframe diagram of each page). These activities were designed for an 11th-grade private school honors English classroom. The first page is an introduction with an incomplete example circuit containing a capacitor, an LED, a resistor, and a battery. Surrounding text walks students through the example. The text does not define each element's physics behavior, but does identify each element by its circuit diagram symbol. This allows for the symbols to be referenced later and helps couple fewer familiar terms (e.g., capacitor) to more approachable symbols, supporting a more intuitive reading of circuit diagrams.

After identifying the elements, students were encouraged to complete the circuit by connecting the battery to the LED (bypassing the capacitor) with the provided copper tape. This simple circuit introduces the idea of a closed loop.

Students then move to the next page, which presents a circuit diagram mimicking the circuit they just built. This gives students a diagrammatic example to build from and shows how to use the "language" (circuit diagrams) they are learning, effectively putting the symbols into a "sentence." Students were then tasked with tearing out every circuit element from this example. These elements are reused on subsequent pages. This interactivity leaves a "ghost" of the example for reference while reducing waste and cost for teachers.

This initial example and diagram provide the first test of student–teacher interaction. Given that students were working with new concepts, teachers needed to be prepared for common questions and troubleshooting. Teachers must recognize LED polarity, ensure proper connections, and emphasize the concept of a closed circuit while visually identifying potential breaks. An accompanying construction and tutorial guide supplies FAQs and best practices.

The third page holds the first major activity. After tearing out the elements from the introduction, students build a specified circuit by taping down the battery with the provided strips and attaching the LED after removing a short wire.

Students experimented with this activity for five to ten minutes before reconvening as a class. The teacher demonstrated two examples either on the whiteboard or via a document camera. The key interactions to observe were: (i) what happens when a resistor is placed in series with the LED and then removed, and (ii) what happens when a capacitor is placed in series with the LED and then removed.

The fourth and fifth pages (Figure 6) contain a writing exercise and a reflection exercise. Before writing in the booklet, students first drafted responses in their own notebooks. Afterward, they collaborated to write a submission for the booklet. This activity focused on similes about circuit elements. In this activity, some students likened the battery to coffee or a wire to a highway.

The sixth page introduces a personification exercise that adds parallel circuitry (Figure 7). Its structure mirrors the previous activity with a group portion, teacher

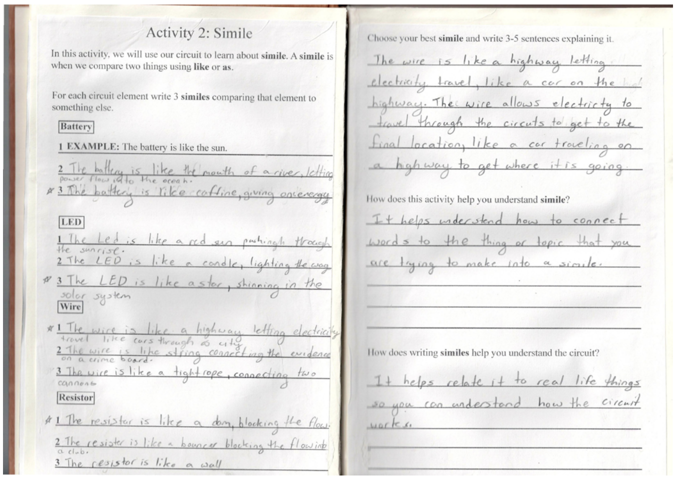


Figure 6. Student simile activity responses and reflections on the activity. Similes with stars next to them are the students' favorite in each group.

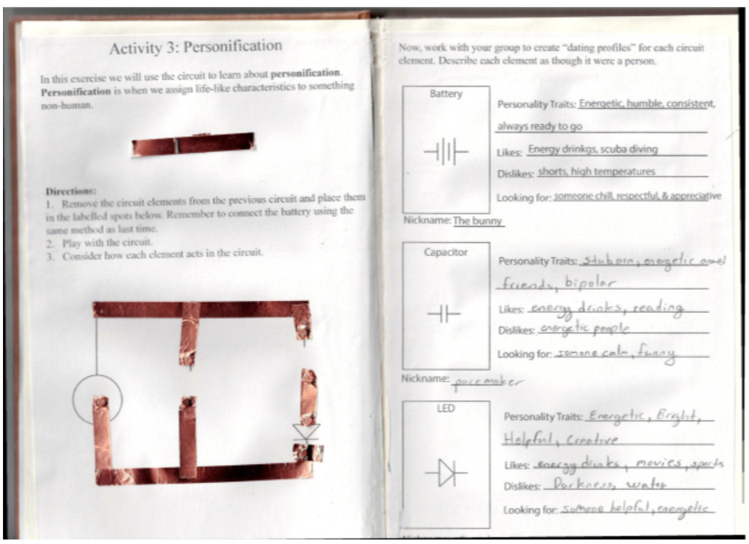


Figure 7. The final booklet iteration with an activity and student responses. Response prompts include the corresponding circuit symbology that students learned in the introduction.

demonstration, additional individual/group work, and a class discussion. This activity was intentionally playful: students created "dating profiles" for each circuit element. While silly, the exercise was designed to engage students in a novel way in English class. An example is provided, and the activity concludes with another reflection.

Additional activities can be added as the semester progresses to support new units. Ideas from teacher interviews included extended analogies, sentence structure, and reading strategies for challenging texts. The first three pages should remain constant, as they introduce circuitry piecemeal; altering them could inhibit students' experiences with the booklet.

5.1.1. English concepts

English comprehension and learning were not the study's goals and were not measured. However, teacher reflections and classroom artifacts are presented as evidence of implementation. This activity booklet was used to teach English using engaging Physics-based materials. The two English topics covered in the existing exercises were simile and personification, as shown in the second and third activities.

From the in-class discussion surrounding these two activities, the teacher reported that students appeared to develop a more solid understanding of the two concepts. When presenting similes, students were able to share their examples with the class, explain why X was like Y, and engage in lively discussions, assigning properties to specific circuit elements. Many groups developed themes and likened each circuit element to an item within that theme. One group was particularly enamored by Marvel and likened the battery to "Infinity Stones," the LED to the "Infinity Gauntlet," and a resistor to Thanos. Another group wrote all Biblical similes, while another wrote similes relating to driving, traffic, and highways.

During the personification discussion, similar themes presented themselves. As part of the booklet, students were required to write an extended paragraph about their favorite circuit element personified. Students were able to envision their chosen circuit element as a personified subject and create stories about it: what it liked and disliked, who its friends were, and what it did for work. This was facilitated by the ease of use of the circuit design, the pared-back number of nodes relative to previous iterations, and the physical affordances the booklet offers through inline annotations and hot-swappable circuit elements. The teacher corroborated these findings in her post-activity interview.

5.1.2. Attitudes toward STEM

Physics comprehension and learning were not the goal of this study and were not measured. However, students' attitudes and beliefs toward STEM were tested through a pre-/post-activity survey (Figure 8, Table 1). There was a noticeable drop in students who disagreed with the statements "I am confident that I can understand STEM subjects" and "I am interested in doing STEM activities in the future." This trend was especially pronounced among female-identifying respondents (n = 12), with Wilcoxon signed-rank values of 0.072 and 0.053, respectively. We hypothesize that this was due to the playful and approachable nature of the booklet and its ability to bring Physics into an already enjoyable subject for these students, though further testing and clarification are required.

5.2. Teacher interviews, input, and experience

Teacher feedback was central to moving *Rock, Paper, Physics!* from a working prototype to a classroom-ready tool. Linda and Candice approached the booklet as intended users: teachers who needed to plan how they would introduce it, anticipate how students would respond, and identify

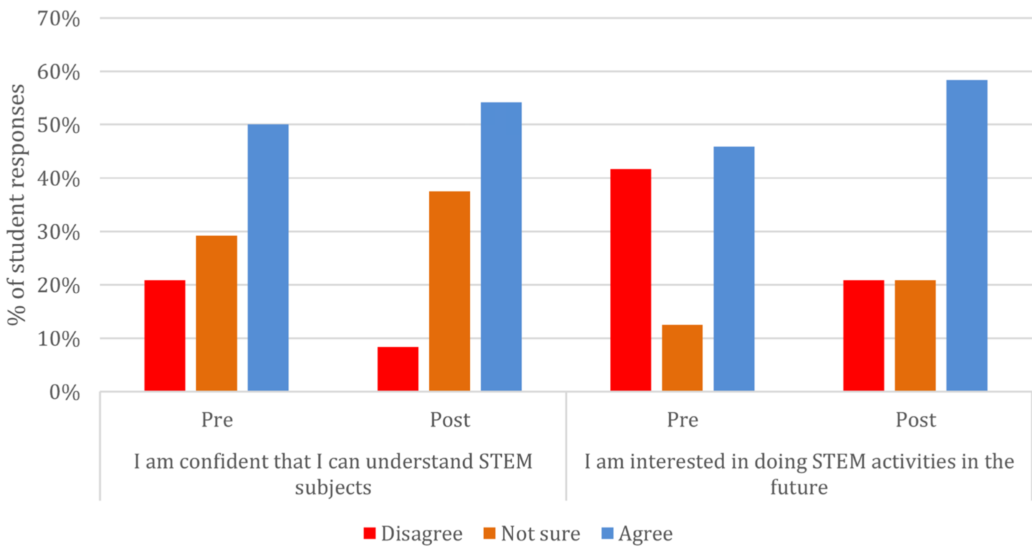


Figure 8. A selection of questions from student pre-/post-activity survey responses
Abbreviation: STEM: Science, technology, engineering, and mathematics.

Table 1. Non-parametric Wilcoxon analysis

Question	Female (n = 12), p-value	Male (n = 12), p- value
I am confident that I can understand STEM subjects	0.072 (borderline)	1
I am interested in doing STEM activities in the future	0.053	1

Note: A non-parametric Wilcoxon statistics table created in Python using the gendered, paired pre-/post-session student surveys. A p-value of less than 0.05 indicates that the difference in the pre-/post-session responses cannot be explained by randomness. A p-value greater than 0.10 indicates that the pre- and post-session responses are similar and may be due to chance.
Abbreviation: STEM: Science, technology, engineering, and mathematics.

where the initial design would create unnecessary friction. Their reactions revealed both the practical barriers of the booklet and the teaching opportunities instrumental to the booklet's success. The interview summaries below capture their experiences and highlight the design changes their input directly shaped.

5.2.1. Interviews with Linda

Linda initially approached the booklet with excitement, which shifted to frustration when some components did not work as expected. On page three, she did not remove the short wire as directed, struggled to secure the battery using rolled tape, and was confused by LED polarity. These combined roadblocks led to a quick loss of interest after about three minutes and required assistance from the researchers.

Once those issues were resolved, she enjoyed swapping various circuit elements. Some configurations were less engaging (e.g., adding all elements except a wire and a second LED in parallel with an existing LED), while others were highly engaging (e.g., placing a capacitor in series with the LED or using two LEDs in parallel).

Linda's main concerns centered on the challenges she experienced during exploration. She worried students would face similar frustrations and felt the introduction was too brief. To address this, future designs included a clearer step-by-step ramp-up: introducing each element individually with descriptors of expected behaviors to look for during play.

After the completion of the finalized booklet study in Candice's high school class, Linda was interviewed again using the new version of the booklet. Linda had much more success experimenting with the circuit elements and experienced much less frustration, as there were no more issues with securing, and the instructions were clearer.

5.2.2. Interviews with Candice

In Candice's first interview, she approached the booklet with curiosity and encountered several challenges, primarily with the LED. At that time, the LED had four terminals, so the battery needed to be connected diagonally for proper behavior. Her initial attempt shorted the circuit through the LED. This was subsequently solved by removing two of the LED terminals in later designs. During the interview, Candice asked insightful questions and diagnosed issues with minimal intervention.

After resolving the first LED issue, Candice discovered that LED polarity: rotating the LED by 180° stopped it from working. Although she did not articulate the underlying reason, she used the observation to troubleshoot future placements.

Once she had experimented sufficiently, Candice brainstormed applications for her classroom, identifying simile, metaphor, analogy, personification, reading comprehension, and paragraph structure/analysis as promising areas. She was enthusiastic about using the booklet and offered to help design future versions. She specifically requested an introductory section on the elements that influenced later designs.

The second interview sought feedback on the redesigned booklet, the pre-made lesson, and an implementation timeline. Candice appreciated the redesign, especially the thin, single-page activities. She envisioned a year-long activity that students could keep and take ownership of.

The third interview focused on idea generation and asked Candice to independently create an activity. She designed the simile activity shown in Figure 6 in about 10 min. She began with the learning goal (simile), wrote the prompt above the right-hand page circuit, and built the circuit using the previous page as a guide, omitting the parallel branch from the prior example. She then laid out the left page as a space for student writing.

On the following page, she asked students to choose their best similes and write three to five sentences explaining them, with an additional reflection space about how the activity supported understanding of both similes and circuits. Candice was surprised at how easy fabrication felt and how quickly she could manage the circuit elements. She demonstrated a solid grasp of current flow and element interactions with minimal interviewer support and agreed with many of Linda's points above.

The fourth interview focused on refining activities, finalizing the classroom deployment schedule, and producing the sketches that led to the finalized booklet (Wireframe viewable in Supplementary File S2).

After deploying the booklet in her classroom, Candice was interviewed again about her confidence in the material and her observations during implementation. During this interview, Candice stated how her confidence in the material had grown, and she felt like she could administer the booklet without aid from the researchers. She was also confident in her ability to design new booklet activities for future English curricula.

5.2.3. Interview similarities

Across both interviews, several common themes emerged regarding engagement, challenge, and pedagogical vision. Despite differences in experience and classroom level, Candice and Linda shared a curiosity-driven approach to the booklet and a desire to see it function as both a hands-on exploration and a bridge to conceptual understanding in English instruction. Both teachers initially encountered technical difficulties with the circuit elements, particularly with LED polarity and component stability, which shaped their early impressions and informed subsequent revisions to the booklet. Each also demonstrated resilience and iterative problem-solving once those challenges were addressed.

Both teachers emphasized the importance of clear, scaffolded instructions. Candice's request for an introductory section to the elements and Linda's recommendation for a "step-by-step ramp-up" reveal a shared recognition that students need structured guidance before open-ended exploration. This was further enforced by findings from the PISEC distribution of the booklet in Section 4.3. Their feedback directly contributed to the inclusion of clearer sequencing and labeled descriptors in later booklet versions.

Both interviews revealed enthusiasm for integrating the circuit-based activity into their English curricula. Candice connected the booklet to figurative language and writing structure, while Linda proposed a magnetic whiteboard model to promote group interaction and student presentations. Candice would have benefited from Linda's proposal as well, as her projector approach during her classroom distribution was less effective. Both ideas reflected an underlying belief in the booklet's potential to enhance engagement through tactile learning and analogy-making.

Finally, both teachers' subsequent interviews demonstrated growth in confidence and familiarity with the materials. As the booklet design improved through addressing issues raised by each participant, both reported smoother interactions, greater enjoyment, and clearer plans for classroom integration. These shared trajectories underscore how iterative design and teacher feedback jointly shaped the evolution of the booklet and its educational value across different grade levels.

5.3. Classroom observations

Many of Candice's interview concerns and classroom reflections were confirmed by our own classroom observations. Using the step-by-step introduction section, students were able to understand the use of circuit elements in the English-centered exercises with minimal teacher intervention. Students finished the introduction activity more quickly than expected and engaged in higher-level discussions about the purpose of the circuit elements, including the directionality of the LED and the function of a capacitor.

Students generally remained on task and, even after completing the assigned task, continued to play with the circuit elements. In students' post-semester feedback to the teacher, three of the 24 students who participated in the activity reported that it was their favorite part of the semester. This highlighted the "play" aspect of the booklet and its novelty in the English classroom.

We also observed Candice's growing confidence and aptitude toward the booklet. She correctly answered questions about the physical properties of the circuit elements and explained how they operated to complete a circuit. She was unable to answer certain higher-level questions, particularly about how an LED generates light and the mechanics of a capacitor, but she did not let these unknowns derail her; she maintained her general air of confidence and commanded the room.

6. Discussion

The development of *Rock, Paper, Physics!* highlights the potential of interdisciplinary design to bridge the divide between STEM and the humanities and shows where integrative STEM may lead in the future. What began as a fabrication challenge evolved into a broader exploration of how physics principles can be reimagined to support non-science learning goals. Iterative testing of materials, circuit refinement, and collaboration with teachers revealed not only the technical feasibility of the booklet but also the pedagogical value of embedding scientific practices in novel contexts.

Original booklet iterations were more costly, afforded fewer user freedoms, and were generally either more confusing or less useful. The "light and color" and "puzzle leaflets" were not engaging enough during user testing and did not aid in teaching English subjects. These leaflets were also less modular and could not be reused or expanded upon. Critiques of these iterations led to the adoption of circuit-based activities with copper tape, magnetic circuit nodes, and variability.

The PISEC booklet iteration lacked focus and direction. It offered more variability for students to play with, but was too open-ended. Users of this booklet tended to become disinterested quickly and required excessive instructor intervention. The manufacturing process had not been solidified, and some of the circuit connections were less than stable, leading to unintentional frustration and broken circuits. Critiques of this iteration led to a stricter fabrication process involving wireframe guides, guided lessons using a step-by-step approach to introduce students to circuit elements, and tailor-made activities designed for specific English classroom curricula, topics, and goals.

Responses from students and teachers underscored the broader impacts of the ultimate approach of the booklet. Students connected circuitry behaviors to personal experiences, imagination, and creative writing, suggesting that scientific tools can inspire new forms of expression and understanding in English classrooms. Teachers emphasized the booklet's adaptability, envisioning applications across diverse units and even year-long curricula. These findings suggest that integrating science into humanities classrooms can help students view learning as interconnected, playful, and transferable across disciplines.

By lowering fabrication barriers and emphasizing modular, low-cost design, this work enhances the accessibility of STEAM initiatives, ensuring that interdisciplinary learning is not limited to specialized programs or after-school opportunities. Instead, it offers a model for integrating science and the humanities into everyday classrooms, enriching both domains. Future efforts should focus on expanding classroom trials, refining scaffolding for different age groups, and exploring additional ways scientific phenomena can illuminate and deepen the study of language and literature.

7. Conclusion

Ultimately, this project demonstrated that when science and the humanities inform each other, students are empowered not only to learn content but also to reimagine how knowledge can be created, expressed, and shared. After the semester had concluded, Candice informed the researchers that two students in her class specifically mentioned how *Rock, Paper, Physics!* was their favorite classroom activity of the year. This was only possible through integrating STEM activities and STEAM educational practices to create an engaging, applicable activity for students.

In the 2025–2026 academic year, the booklet is being implemented in one school. Candice is distributing the booklet in the same private high school classroom as the 2024 distribution, with the same activities, and is also distributing it in a higher-level English classroom with the same students who participated in the study in 2024, with additional activities. We plan to compare the responses of the new students with those of the 2024 distribution, and conduct a longitudinal study of the previous students' attitudes and beliefs toward science. We also plan to study what courses these continuing students enrolled in at the start of the 2025–2026 academic year and how they relate to their previous responses.

One area currently being pursued is the study of the booklet in a public school classroom setting. This would allow us to determine how different student populations affect outcomes and whether findings from the previous distribution are generalizable across student demographics and age ranges.

One area that has not yet been pursued, but remains of interest, is the use of conductive printer ink. While initial testing found it to be too costly and complex, it still offers the potential for mass production, which would be highly beneficial. Using conductive printer ink to mass-produce a sellable activity booklet could be a viable alternative to having teachers manually create the booklet for their students.

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Writing–review & editing: All authors

Ethics approval and consent to participate

All research in this article was approved by CU Boulder's IRB, protocol #24-0037. Written consent, assent, and letters of cooperation were obtained from all parents of students, students, teachers, and the school boards involved.

Consent for publication

Written consent for publication was obtained from all participating parents, students, teachers, and the school boards involved.

Availability of data

Data from the study can be obtained through the supplementary files or by emailing the corresponding author.

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