Papertronic Puppets: Teaching STEM and Storytelling Through Creative Construction

Sarah Kushner, John Kanji, Paul H. Dietz, Daniel Wigdor
Dynamic Graphics Project Lab, Dept. of Computer Science
University of Toronto
Toronto, ON Canada
{sak,jkanji,dietz,daniel}@dgp.toronto.edu

***Abstract*—This innovative practice full paper finds that storytelling through animatronics can offer a combination of creativity and engineering in order to engage students in an inquiry-based approach to STEM learning. Animatronics is the art and science of bringing a story to life through robotic puppetry. Typically reserved for trained engineers with ample resources, animatronics can be an expressive yet inaccessible medium. We aim to allow students to write, create, and perform an animatronic story, learning valuable technical skills along the way. Our study, which took place over the course of eight weeks, investigates the use of our Paper Animatronics Kit in a Grade 2 and Grade 6 classroom, following the progression of their creative writing, animatronic building, and mentoring processes. We present results of our qualitative analysis of student and teacher interviews and group discussions.**

***Index Terms*—K12, Creativity, Communication skills, Problem solving, Student experience**

I. Introduction

Stories are the medium by which we decode the human experience. Storytelling has been discussed in the context of education as a way of cultivating imagination, empathy, and reflection of the world [1]. Through writing and performing, students build a literacy of storytelling which lays the foundation for deeper, more complex engagement with the world.

Animatronics is the art and science of building physical robotic puppets to bring a story to life with sound and motion. Animatronic shows have become a fun and popular attraction in theme parks, restaurants, and museums, ever since one of the first presentations to the public, Walt Disney's life-size animated Abe Lincoln at the 1964 New York World's Fair. This expressive practice is a unique combination of creativity and STEM (science, technology, engineering and math), which makes it a useful tool to engage students in both storytelling *and* robotics.

However, this expressivity comes with a high barrier to entry, and the medium is typically accessible only to trained engineers with ample resources. To help lower this barrier and make animatronics accessible to a wide range of ages, abilities, and socioeconomic status, we introduce an affordable yet versatile Paper Animatronics Kit for K-6 students to create papercraft puppet shows. The design of our kit is informed by the "critical making" movement established by thinkers such as Ratto and Garnet to describe the process of creating artifacts to explore and understand social and cultural issues, blending engineering, design, art, and social sciences [2], as well as Resnick's idea of "tinkerability," which he defines as "a playful, exploratory, iterative style of engaging with a problem or project" [3]. Critical making and tinkerability are not focused on the product of the making but the process of getting there which acts as a way for the maker to explore the world. By centring storytelling and the creative process, and allowing open-ended exploration with the technology, we aim to empower student agency and voice. Our kit thus uses an inquiry-based approach that taps into students' genuine curiosity about the world to solve problems, scaffolding the technical elements while allowing them to tinker and inject their creativity and identity.

Our contributions are as follows:

- A Paper Animatronics Kit for K-6 students
- An in-classroom user study with Grade 2 and 6 students to evaluate the suitability of our kit
- Qualitative analysis of teacher and student interviews and group discussions

In this paper we describe the components of our kit in more detail, present the findings of our study, and end with key implications of using our animatronics kit in elementary classrooms.

II. Related Work

A. STE(A)M, and the Creativity Gap

Of central importance to us is the so-called "creativity gap," defined as "an incongruity between the ostensible value educators place on creativity and its absence in schools" [4]. The creativity (or creative participation) gap manifests in education in a variety of ways: the removal of creativity from "academic" subjects and its partitioning into separate arts programs, and the chronic underfunding of said programs [5], but also inequity of access to experience, skills, and tools required to flourish creatively in an era of digital media [6].

Emerging as an augmentation to the interdisciplinary field of STEM, STEAM aims to address the creativity gap by integrating the Arts into STEM education, emphasizing creative and design thinking as well as problem solving [7]. But this approach has been problematized by some, such as

Mejias et al. [8], who argue that STEAM education fails when either arts or engineering takes precedence over the other; introducing STEAM in a nuanced way proves challenging. Liao, on the other hand, argues for a transdisciplinary, arts-integrated approach which is centered on "the creation of art that is simultaneously applied work" [9]. Motivating STEM tasks with creativity promotes student voice and choice, which inspires students to make something they truly care about and are proud of.

B. STEAM Education in Action

The implementation of STEAM education varies; some programs aim to integrate robotics into the classroom, which requires planning and teacher training. The "Arts & Bots" program aims to increase empowerment and inclusion in STEM disciplines by integrating robotics into middle-school core subject classes [10], pairing the Hummingbird robotics kit with a custom software programming interface. The Arts & Bots team has conducted a series of user studies with teachers and students to uncover student learning outcomes and attitudes toward STEM [11], and the challenges teachers face when planning and implementing the program [12]. Although teachers were mainly successful in their attempts to combine robotics with their course material, they found that the nature of subject-specific curricula constrains teachers' pedagogical choices, limiting opportunities for open-ended storytelling. Additionally, controlling the robots requires coding skills, adding to the teacher training required [13].

Many commercial robotics education kits exist, such as Hummingbird [14], used in the Arts & Bots program, which targets Grades 4-12 and includes compatibility with the micro:bit, and littleBits [15], a system of modular pre-assembled circuit boards which snap together magnetically, making it accessible for young children. These kits usually include various sensors, servos, and LEDs. Although versatile, they are very expensive, generally costing over $1000 to outfit a classroom, making access infeasible for schools without the means to buy them.

Additionally, numerous after-school programs and summer workshops incorporate robotics into creative tasks, such as an upper elementary robotics program that designed an animatronic zoo [16], and a program for middle-school girls to build expressive robots [12]. However, while extra-curricular programs such as these motivate young people to engage in creative and design thinking, they are prone to the same inequities of access that drive the creativity gap [17].

C. Motivating STEM Through Animatronics

While much research has focused on integrating creativity into STEM through visual art, another compelling avenue for student expression is through storytelling. Incorporating puppets into storytelling is a way of "making the story come alive" and can give kids new perspectives on, and relationships with, stories [18]. Animatronics and puppetry provide a natural entry point for the integration of STEM with storytelling and creative thinking. Robotic puppetry has been found to engage children in storytelling by allowing them to take an active role in the story, for example, by inviting kids to interact with the puppets during the story [19], or having the kids do the puppeteering themselves [20]. Huang et al. describe a 5-day workshop with 11-13 year-olds who created interactive "e-crafts" and accompanying written stories [21], finding that storytelling allowed student to inject their own interests and identities into their learning, deepening their engagement with the STEM and design tasks. Alford et al. used robotics to combine STEM with drama, hosting a 3-day animatronics workshop where high school drama students wrote plays and built and programmed their own robot actors [22]. Their workshop, while very demanding in terms of the materials and expertise required, demonstrated the potential for animatronics to serve as an outlet for children's creativity.

There is a need for affordable technical supplies in order to participate in animatronics or any of the aforementioned STEM tasks. Papercraft has been explored as a low-cost medium for students to experiment with robotics. Systems like AutoGami [23] and FoldMecha [24] provide software for students to design and program moving paper creations. While AutoGami has been used for more representational papercraft, artifacts made with FoldMecha are closer to paper automata with electronic actuators. These kits challenge kids to come up with creations involving electronics, but none focus on storytelling, causing the creative elements to take a back-seat to the mechanical challenge.

D. Collaborative Making

Dieter and Lovnik, in their Theses on Making in the Digital Age, state that "[t]he maker is always plural. We all know we never make things alone... We feel a constant pressure to invent and discover new tools to support collaboration" [25]. Cross-age peer mentoring is a collaborative model which been explored in education as a means of mobilizing student knowledge and building social-emotional skills. Students also benefit from developing friendships, gaining confidence, and strengthening knowledge and skills [26].

Boling et al. explore cross-grade mentorship in outdoor education, pairing students from Grades 6 and 3 during a field trip to study water quality of a local river. They find that engaging in mentorship "deepens interest, investment, and ultimately ownership of new learning" for both the mentor and the mentee [27]. In the context of STEAM education, Tenhovirta et al. studied cross-age tutoring in a maker-centered lower secondary school, examining mentor/mentee relationships within teams of students working on a collaborative design task [28]. They found that "young people have impressive sociodigital skills that could provide valuable social learning resources when their use is legitimised through peer tutoring practices."

III. ANIMATRONICS KIT

One of the key contributions of this work is the Animatronics Kit, a low-cost educational kit combining creativity and STEM tailored for use in elementary classrooms.

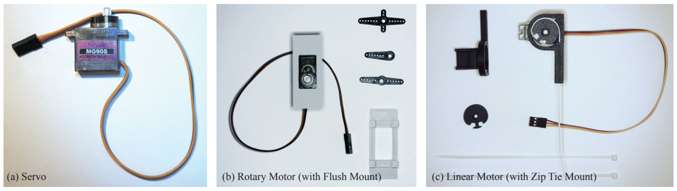

Fig. 1. The servo (a) is about 30 x 30 x 12 mm. The Flush Mount (b) allows for rotary motion. The Zip Tie Mount (c) allows for linear motion.

Our kit is designed to make creating convincing talking paper robots with synchronized sound and motion accessible and fun for young students. While it is specialised for the assembly of an animatronic show rather than providing more generalised functionality, this focus allows it to be more affordable and streamlined compared to mainstream robotics kits. Along with ease of use, cost is a major factor in accessibility. Our most expensive board costs about $7 USD to produce in 50 unit quantities, allowing us to offer these components at prices that are highly competitive with inexpensive Arduino-based kits that have found wide adoption in schools.

Each kit consists of one Linear Motor, one Rotational Motor, three printed circuit boards (PCBs), and a battery pack. We also provide template animal characters from Woo! Jr [29] printed on 8.5 x 11" heavy-duty paper, as well as double-sided tape to attach the Motors to the cardboard or paper puppets. We assume classrooms have access to common crafting materials and tools such as scissors, glue, card stock, etc.

Each of our Motor units comes pre-assembled and comprises a small electronic servo, a type of motor common in hobby applications such as robotics and model aircraft, and a custom-designed 3D printed mount to allow easy attachment of the servo to the puppet (see Fig. 1). The Rotational Motor unit includes three different horns (in black) that clip onto the shaft, which provide a small surface area to attach the moving element of the puppet. This allows the user to create swinging motions such as a waving arm or a kicking leg. The Linear Motor mount includes a small mechanism to convert the servo's rotational motion into linear motion, with a zip-tie to attach the moving element. This motor is intended to allow the creation of talking characters whose mouths move up and down, but it has many more applications such as as a punching arm, or even a grasping claw.

To control the motor we have designed three circuit boards (See Fig. 2) customized specifically for the purpose of animatronic storytelling through puppetry. They are intended to scaffold students' understanding of the features and slowly introduce new capabilities.

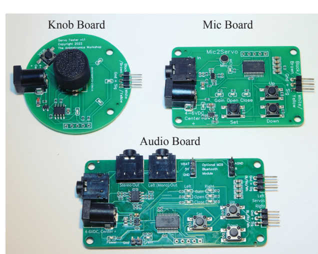

Fig. 2. Our boards allow users to control the motor in different ways.

The three boards work similarly in terms of connecting and configuring: the motor plugs into a 3-pin connector on the right side of each board, and a battery pack with four AA batteries plugs into the jack on the left side of each board, seen in Fig. 3. Buttons on the board allow the user to adjust the range of motion by setting the maximum "open" and "close" positions, which are saved for subsequent use.

Where the boards differ is in how they allow the user to control the motion of their puppet. The first and simplest is the Knob Board, which lets the user directly control the motor shaft angle using the knob. It also has a "sweep" mode, which automatically spins the motor back and forth between its full range of motion with variable frequency.

The Mic Board uses an on-board microphone that the user can talk into, rather than controlling the motor using a knob. The motor moves proportionally to the volume of the audio input, allowing the user to perform live shows with the puppet. This board additionally allows the user to configure the gain, the amount the motor moves for a given volume of input, which can help when the puppeteer is in a noisy classroom. Most complex is the Audio Board. Similar to the Mic Board, this board responds to sound, but includes a 3.5 mm audio input jack in place of a microphone, allowing students to play recorded audio to create pre-recorded scenes and skits. The board also includes an audio output, allowing the user to pass the audio to an external speaker when presenting. This board additionally includes two 3-pin connectors, allowing two motor units to be controlled simultaneously and independently. For the Animatronics Puppet Kit this feature was simplified to ensure accessibility for young children by making the two motors move in unison.

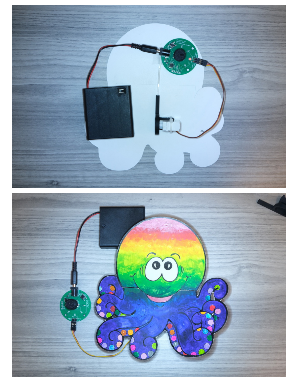

Fig. 3. An assembled puppet.

IV. School Workshop Study

The goal of our user study was to evaluate the kit's effectiveness in three key areas: the ease and comfort for teachers to implement it in their classrooms, the ease of use and expressivity for students, and the identification of mechanical or technical aspects that required improvement. We conducted a series of in-classroom user studies at an urban independent K-6 school affiliated with the authors' institution and located in a major Canadian city (*the lab school*). We have approval of our ethics protocol through the REB at our institution as well as the board of the lab school in which we conducted the study. To preserve participants' anonymity all names have been changed.

A. Pilot Study

Working with the school's Tech Teacher, Ricardo, we began with a one-session pilot study with a class of Junior Kindergarten (JK) students (aged 4-5) to validate the parts of the prototype kits, and established a collaborative relationship with Ricardo, who worked closely with the research team throughout our time at the lab school. Ricardo, who is also the school's Special Education teacher, has a personal interest in technology and helps integrate technology into the classroom on a case by case basis with all grade levels. He led the JK students through a series of lessons, starting from "What is a puppet?", leading all the way to each student creating their own paper animatronic character. The students performed short stories with one line of dialogue using the Microphone Board. This pilot demonstrated to the research team that the parts in the kit not only were understandable for very young children, but were also robust to rough handling.

B. Participants

Our participants comprise the students and teachers of two classes at the lab school: a Grade 6 class and their teacher, Anita, and a Grade 2 class and their teacher, Sonny. Teachers signed consent forms to be interviewed before and after the process of facilitating the workshop. Parents of the students in the classes signed consent forms giving permission for data collection of audio, video, and photo of the students and their creations, and were given the option to blur photos and alter audio recordings of their child in publications.

Grade 6 teacher Anita has a background in Kinesiology and 22 years of experience teaching across grades K-8. Working initially as a physical education teacher before transitioning to being a classroom teacher, she has completed professional development in reading and elementary science. In our pre-interview with Anita she discussed her enthusiasm for cross-curricular integration in her teaching. Her class consists of 24 students between the ages of 11 and 12 (12 girls, 11 boys, 1 non-binary).

The Grade 2 teacher, Sonny, has an undergraduate degree in history with a minor in biochemistry. After working as an outdoor education facilitator he decided to get his Master's of Arts in Child Study and Education, and has four years of classroom experience, also having worked as a phys. ed. teacher, as well as an occasional teacher, and now as a Grade 2 teacher in the lab school. He discussed with us the importance of understanding each of the unique learners in his classroom, and his teaching emphasized student voice and choice. The Grade 2 class had 22 students between the ages of 7 and 8 (11 girls, 11 boys).

The two teachers participated in a 45-minute unrecorded Teacher Training session in which they had the opportunity to explore the animatronics kit themselves. The research team went through each board, explaining how to access and change the settings and how to plug them into the battery pack and motor. The teachers each made an animated puppet character using pre-made characters printed on card stock. They were able to quickly grasp the idea of how to use the components in the kit to make a puppet. The research team left the kits with the teachers so they could continue tinkering with their characters.

The teachers consulted with the research team, but were given a large degree of independence to introduce the animatronics kits into their classrooms in the manner they thought best. As the two classes had an established cross-grade mentoring system, each Grade 6 student being paired with a Grade 2 "special friend," the teachers were enthusiastic to incorporate this mentorship aspect into the workshop, and collaborated closely when planning their instruction. This also informed our research question about mentorship and prompted us to craft interview questions for students and teachers to investigate its role in the experience.

C. Interviews and Group Discussions

We conducted individual semi-structured interviews with both the teachers and the students. In order to get a sense of the background and interests of our teacher participants, we conducted one-hour interviews (*pre-interviews*) with each teacher before beginning the study. At the conclusion of the workshop, once most of their students had completed and presented their puppet shows, we conducted 30 minute interviews (*post-interviews*) with the teachers to debrief them and hear their observations and feedback on the workshop and the kits, and their suggestions for improvements.

In addition, we collected feedback from the students through two ten-minute whole-class group discussions with the Grade 6 students, and a number of short, individual or small-group semi-structured interviews with a handful of students from each class, each lasting approximately 5-10 minutes. Students were selected to be interviewed from those who had finished creating their puppet shows on the basis of teacher recommendations and student interest. In total, we spoke to nine Grade 6 students over six interviews, of which two interviews comprising four students were discarded, and ten Grade 2 students over seven interviews, of which none were discarded.

D. Data Collection

Throughout the Animatronic Puppets Workshop we collected a variety of multi-modal data. During all sessions, students' work was documented through photos and videos showing their creative process and work-in-progress. Researchers circulated among the students to observe, provide support, and to chat informally with them about their process and their experience with the kit. In addition, we collected video and audio of the whole room during Grade 6 group discussions, but the video portion of this data proved unusable and was discarded.

All data were anonymised and stored digitally on a secure cloud storage service, and only those members of the research team directly involved in the data processing and analysis were given access. Audio recordings were automatically transcribed securely on the researchers' device using OpenAI's Whisper algorithm [30]. These transcriptions were then manually verified by a member of the research team.

E. Coding and Thematic Analysis

We performed an iterative process of coding and thematic analysis [31], [32] on the transcripts from the interviews and group discussions. Two researchers independently performed two rounds of open coding on the transcripts, each followed by discussions to ensure inter-coder agreement. These codes were then analysed over three collaborative sessions in which the research team reviewed all the codes and artifacts to identify salient themes which we developed into the key implications we discuss in Section VI.

V. Findings

For our main study we worked with two classes, one Grade 2 and one Grade 6, over 13 sessions across a period of approximately eight weeks. We organize this section by groups of sessions with each grade, including the two special friends sessions when they worked together.

A. Session 1 - Grade 6 Exploration

In the first 1.5 hour session, Anita, supported by Ricardo, introduced the kit to her students using an inquiry-based approach. The Grade 6 students each were given a Linear Motor, a Mic Board, and a battery pack, and tasked with independently figuring out how to assemble the parts and exploring how the kit works, including using their voice to actuate the motor, and changing the settings of the board. Once students were familiar with the basic functionality they were then asked to create a character out of paper. Students were given the freedom to create whatever they wanted, and they found inspiration from many sources, basing their puppets on animals, characters from popular culture and even each other. Anita chose to offer students struggling for inspiration the option to use template characters provided in the kit, but only two students chose this, and Anita did not provide this option going forward, preferring to encourage students to create their own character. Some found the suggestion to make a talking character limiting and we saw many creative applications of the Linear Motor in papercraft mechanisms such as Leo's Whack-a-Mole game, or Ryan's face with an animated tongue (see Fig. 5). In the busy classroom, some students grew frustrated at the lack of control offered by the Mic Board, which they found to be too sensitive for the noisy classroom environment. We thus offered all students the option to use the Knob Board, which provides more direct, manual control. After students had built their puppets they performed improvised skits for the class, either alone or in groups.

To close the session, Ricardo led a group discussion asking students what they found enjoyable and difficult. Students described their approaches to design and construction. One student, Francis, discussed the creative compromise he had to come to when assembling his puppet, saying "we wanted people to see the full drawing so we ended up putting half of [the motor] actually showing." Another student, Sasha, reported frustration

Fig. 4. Grade 6 student Sasha creates a puppet with her special friend.

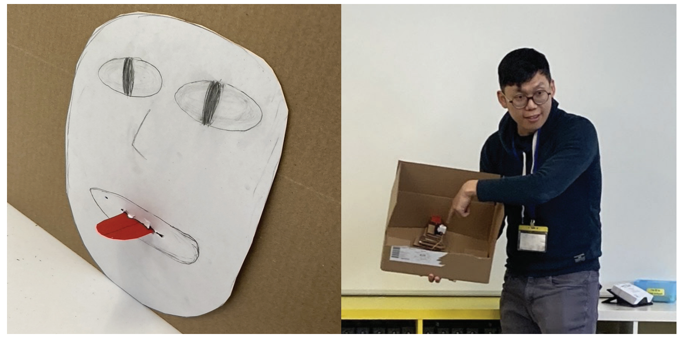

Fig. 5. During a class discussion, tech teacher Ricardo highlighted the problem solving steps Grade 6 student Ryan followed to make the tongue of his puppet move in and out using the Linear Motor.

with the Mic Boards due to latency and sensitivity, recounting that "I would have to have people around me be quiet so that it would stop moving and it would still go from little sounds" but despite this, she enjoyed the ease with which she could bring her vision to life, continuing, "it was also really satisfying and easy that all you have to do is take the machine and just plug things in and make a puppet."

B. Session 2 - Special Friend Teaching

In this 40-minute session facilitated by Anita and Sonny, the Grade 6 class was joined by the Grade 2s and students broke off into *Special Friends* groups, pre-assigned cross-grade mentorship pairings. Each group was given a battery pack and could choose to use either the Knob Board or the Mic Board, and either the Linear Motor or the Rotational Motor. Students were tasked with inventing a character and turning them into an animatronic puppet, with the Grade 6 students guiding their Grade 2 partners on the use of the electronic components, as seen in Fig. 4.

After 30 minutes the Grade 2s returned to their classroom, and one of the researchers led a group discussion with the Grade 6s reflecting on mentorship experience. We asked the Grade 6s which of the boards they used with their special friend. Most students who responded said they ended up using the Knob Board ("the twisty one") over the Mic Board ("the talking one"). Consistent with their experience from the previous session, students found the Mic Board hard to control, with a student reporting "it would respond too late and it would make random movements" Another student, Cindy, recounted that she initially used the Mic Board, but switched to the Knob Board because the extra buttons distracted her special friend. Students reported that the Knob Board gave them more precise control and that they could more easily understand the correspondence between their input and the resulting motion. In addition, some students preferred the Knob Boards because of the automated sweep feature. However, the Mic Board seemed to spark a particular sense of wonder in the younger Grade 2 students. Sasha picked it because her special friend wanted to try it:

> I think it was more fun for her, because she got to– I don't know. She just really enjoyed getting to speak

> and seeing its mouth move, and I think it was just kind of cool. The twisty one, it makes a lot of sense, it's like you twist this and it goes up and down. But the talking one is more magical and fun when you talk and it talks.

C. Sessions 3-5 - Grade 6 Writing and Puppets

Over these three one-hour sessions, the Grade 6 students worked individually or in pairs to develop a final puppet, choosing either to further develop the puppet they created with their special friend, or to develop a puppet based on a character from the stories they had been writing in their literacy class. The sessions were led by Anita, and Ricardo was present at one of these sessions to provide additional support.

As the students' confidence with the kit grew, so did the sophistication of their creations. Working with characters in which they were already invested, students employed creative design to create puppets which fit into settings of their own invention. Leo described how he choose to bring the giant worm from his story to life: "I picked which character would look good moving, and I thought about which characters would be able to move easily."

Students who completed their puppet early and were seeking more challenge were invited to use the Audio Board to create an animated skit. Using a classroom laptop and an online voice recording service students were able to record lines of dialogue which, when played back through the Audio Board, animated the puppet. While experimenting with playing different audio through the board, Leo and Hiro tried playing music, hoping it would look like the puppet was singing but were disappointed to find that the puppet's mouth simply opened wide when the music played. Leo later recounted how this experience deepened his understanding of the technology: "with the song, it's not speaking the lyrics. It's just open when there's noise, . . . and then it's shut when there's no noise."

While some students, such as Leo and Hiro, put their efforts into developing the technological complexity of their puppets, other students focused on refining the artistic components. Cindy spent the majority of her efforts carefully drawing her cartoon rocketeer. She used the Knob Board's sweep function to automatically animate the rocket's flames.

D. Session 6 - Grade 6 Puppet Show and Tell

In this 30-minute consolidatory session, which concluded the Grade 6 students' involvement in the workshop, the Grade 2 class once again joined the Grade 6s, two weeks after the initial mentoring session to see their special friends' finished puppet shows. The Grade 2 students had already begun brainstorming stories and characters for their own puppets at this point, and this session gave them an opportunity to draw inspiration from their Grade 6 peers. At the same time, the Grade 6 students had the chance to see the culmination of the efforts in creating their puppets as they brought them to life for the audience of their special friend. The Grade 6s used their puppets, as well as voices and gestures, to breathe life into their stories. Some students additionally used an online digital storytelling tool, StoryJumper, to enhance their performance.

Fig. 6. Simone presents her finished puppet show to her special friend.

Near the end of the session, Grade 6 student Ryan created an animatronic bird with a few others, at the suggestion of his special friend. Telling us that he "was used to microcontrollers," he made use of the Audio Board's two motor outputs to connect a pair of Rotational Motors to act as flapping wings. Other students contributed artwork for the bird's wings and head, and Ryan recorded an onomatopoeic sound effect, "*flippity-flappity*," to animate the wings (see Fig. 7), delighting the Grade 2 students as they flapped back and forth.

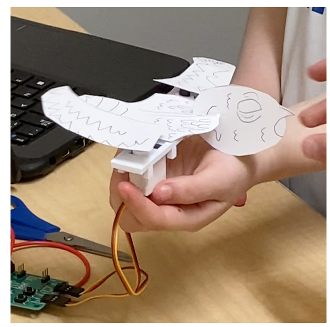

Fig. 7. Ryan's double winged bird.

E. Sessions 7-13 - Grade 2 Puppet Shows

For the remainder of the workshop the Grade 2 students used the kits independently, working on their own puppet shows. For each of our sessions with the Grade 2 students, facilitated by Sonny, we worked with half-groups of 11 students at a time. Ricardo was present at two of these sessions for support and observation. We worked with each half-group three times over six 1 hour sessions, supporting them as they developed their characters into puppets. Group instruction was largely the same between half-groups, and students worked at various paces in pairs or small groups.

Sonny began with each half-group by (re-)introducing the components of the kit, asking if they remembered their names and how they connected together. Despite the fact that the Grade 2 students had not received direct instruction on the kit, they were able to describe the purpose of the motor, board, and battery, and how to connect them, due to the hands-on experience with their special friends. They were easily able to recall how to use the boards they had familiarity with (either the Knob Board or the Mic Board) and were able to immediately begin creating puppets. They were tasked with picking a character from their story and bringing it to life.

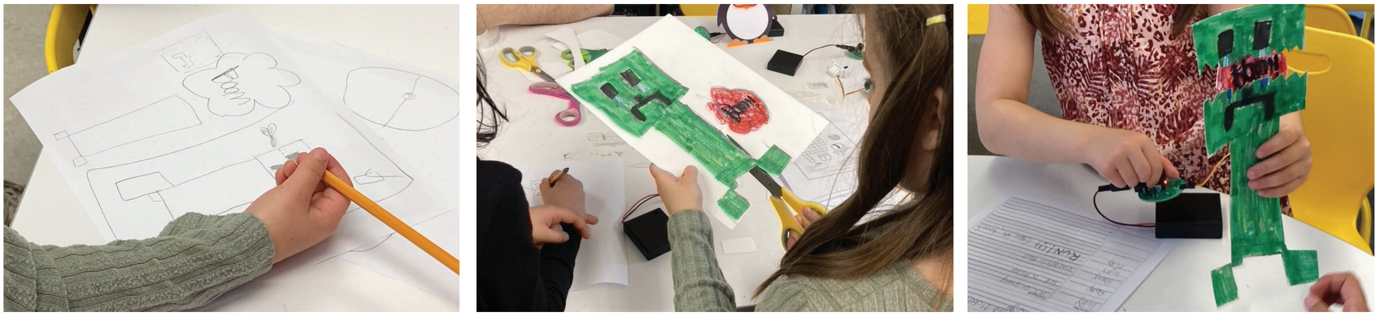

Fig. 8. The progress of Grade 2 student River's Minecraft creeper puppet character named "Boomy McBoomerface."

Compared to the Grade 6 students, who generally only needed help when facing technical problems such as flat batteries, the Grade 2s needed more teacher support. In particular, attaching the motor to the paper cutouts proved taxing to the students' fine motor skills. This was partly exacerbated by the small size some students drew their characters on the card stock, and after the first pair of sessions Sonny chose to make an exemplar puppet available to students based on one of the templates provided with the kit to give them an idea of sizing.

As the students began completing their puppets, Sonny had them form small groups of 2-4 and collaborate to write a cross-over script where each of their characters meet. As we saw with the Grade 6 class, students engaged with the kit in different ways; some were driven by the making, such as Amir, who was determined to build a tripod to allow his alien puppet to stand while it talked, as seen in Fig. 10.

For some students it was the creative aspects that engaged them. Some focused their efforts on drawing the art for their puppets, or designing scenery to enhance their shows. Others were drawn in by the script writing element; one pair of students, Rose and Bernadotte, decided as they worked on their script that their story needed "something evil." This led them to create a new puppet, a villainous troll swinging an animated spiked club (see Fig 9).

In the final sessions, Sonny encouraged each group to spend time putting the final touches on their creations. Some groups focused on adding to their script, some chose to spend time designing the set and props from cardboard pieces, and others wanted to perfect their character puppets with structural additions. The Grade 2 animatronics activities ended with a performance of their scripted shows in front of the class.

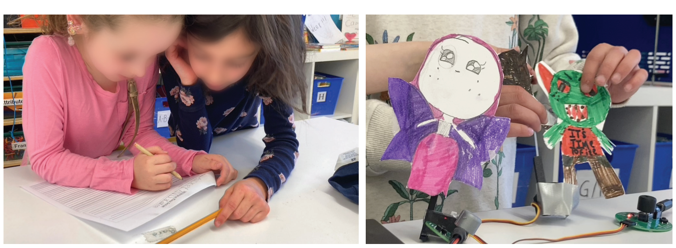

Fig. 9. Rose and Bernadotte write a script with lines for their troll character.

VI. Discussion

We discuss our takeaways from the study centered around the four major themes which emerged from our analysis process: creativity, challenge level, benefits of cross-grade mentoring, and suitability of the kit for elementary classrooms.

A. *Combining Creativity and STEM with Puppet Design*

The focus on storytelling opens up endless creative possibilities. The parts in our kit were originally designed for the purpose of animating the mouths of talking characters. Perhaps unsurprisingly, the students immediately found creative ways to incorporate the simple linear motion to animate their characters, such as a pogo stick, a Whack-a-Mole game, and an ice cream cone. In the words of Grade 6 student Ryan, "there's pretty much no limits."

The open-endedness of the character design task provided student choice while allowing students to practice design thinking and problem solving. All the participants appreciated the creative freedom the kit afforded students. Both Anita and Sonny expressed in their post-interviews that students were highly engaged, and some threw themselves into the process of creating a character, writing a story, and designing and crafting the puppet. Students were able to bring their own interests into the stories, whether it be from popular culture or something more personal. Several Grade 2 students drew inspiration for their stories from video games like Minecraft (for example in Fig. 8). Sonny remarked that "motivation comes from different places. It's really exciting for them to bring something like a character that they like to life."

Ryan's experience with STEM allowed him to understand the input and output of the Audio Board with no instruction, and independently create the bird in Fig. 7. Charlie, who had knowledge of origami, showed his special friend how to make a 3D papercraft claw, which he actuated using the Linear Motor. But while these students were able to leverage knowledge from extra-curricular experiences, the majority of students, even in the Grade 6 class, struggled to find innovative applications for the kit, which could imply that creative mechanical design is not well scaffolded in the curriculum. Even using the components currently provided in our kit, it is possible to create more interesting motions, but few students possessed the engineering skills to experiment with them. Further research is needed to work towards equipping kids with these valuable skills.

B. Challenge Level and Suitability for Elementary Students

The kit provides a suitable challenge for younger elementary students, but lacks the technical complexity to deeply engage older kids. One of our goals in providing easy-to-use PCBs specialised for animatronic puppetry is to lower the technical barrier to entry to begin telling stories, and the "plug-and-play" connectivity of components in our kit supported this. Anita said, "once [the Grade 6s] had that first kind of lesson and their questions got answered, then they were off. So, it was a quick learning curve." Sonny told us "the benefit of having it so programmed is that it makes it really accessible."

The trade-off to having an easy-to-use kit made specifically for animatronics is the lack of open-endedness on the technical side, and students found that the fixed functionality of the motors and boards limits the complexity of possible creations. In our group discussions, the Grade 6 students expressed a desire for more complex types of motions and motor mounts, possibly akin to the gear systems used in [24], which would widen the design space. Anita also noted that the students "want to be more involved in the technology and the innovation of it," and suggested including details on the design of the PCBs themselves in future iterations of the kit. We were not able to include the Audio Board's feature giving independent control of two motors, because we could not install necessary software on the students' laptops. This could have provided a next step in the progression of difficulty through our kit.

In contrast with the older kids, Sonny's Grade 2 students were sufficiently challenged by the character construction. Mechanically planning the design proved difficult, but in a good way. Sonny reflected, "That's awesome engineering problem solving for them. Trying to realize a character in those constraints is really good learning." Grade 2 students also struggled with motor skills required to physically build the character. River told us that cutting out the small pieces of the legs of her Minecraft creeper was the hardest part, but was rewarding too. She said that her favourite part was "seeing what it would look like when [she] was done."

C. Students Becoming Teachers

Cross-grade mentorship provides benefits for mentors and mentees, increasing engagement and providing students with opportunities for social-emotional growth. Anita spoke of the value of the creative partnerships in brainstorming and community-building, saying, "It was nice seeing them. The special friends were helping the bigger kids… I thought it was a really good relationship, bouncing ideas off one another." She described how the the Grade 2s provided direction on "how they would want the animatronics to work, like how fast, how slow. How it should move." Students also reflected positively on the experience. Sasha described seeing herself as a teacher: "It was kind of cool to hear myself explaining it to her … because I hadn't really– I just kind of knew it in my mind, but it was cool to hear myself explain it." Thus, despite the lack of challenge felt by some of the Grade 6s, authentic motivation of creating a story for their special friend led to deeper and more sustained engagement.

Fig. 10. Grade 2 students perform their puppet show for the class.

Sonny reflected that having the experience with their special friends gave the Grade 2s a familiarity with the parts that allowed them to begin constructing characters independently right away. It also gave them examples of what a successful working puppet looked like, which guided their own design and building process. The collaboration with the Grade 6s provided direct inspiration for the Grade 2s' creations. For example, after seeing her special friend build a character swinging an axe with a Rotary Motor, Grade 2 student Fatima used a Rotary Motor to make her character swing a makeup brush in the same way. Another Grade 2 student expressed a very strong interest in using the Audio Board after seeing his special friend use it. Seeing their special friends work on animatronics also provided another source of motivation for Grade 2s, with the Grade 6s acting as role models. Sonny highlighted the intrinsic motivation for his students in working with older kids, saying, "I think that feels, you know, exciting for younger kids to feel like they're doing things that older students are doing."

D. Insights into Classroom Kit Evaluation

The classroom environment is often chaotic and busy, and the classrooms in our study were no exception. One difficulty this introduced was the frustration students felt using the Mic Board, with many reporting that it didn't move the motors the way they expected it to. Students preferred boards which they felt gave them more control. Many students, especially in Grade 6, chose to use the Knob Boards or even the more complicated Audio Boards, instead of the Mic Board, indicating room for improvement on the technical implementation and interface of the mic board. Perhaps a push-to-talk button similar to walkie-talkies would alleviate the unwanted microphone response from other noises in the room.

In terms of character movement, some students encountered problems based on the materials they used to make the puppet. When students taped larger pieces of card stock paper to the zip tie, it would bend and twist, preventing the puppet from moving properly. In his post-interview Sonny said, "if it gets too big, it gets so floppy because like the motor's so small, there's not a huge backing to attach it to," demonstrating the need for a more rigid attachment than a zip tie. In one case, Sonny cleverly taped a popsicle stick to the zip tie, allowing the student's puppet to move the way she wanted.

Students also ran into technical hurdles with the motors. One type of servo we had developed a jamming issue, which occurred occasionally during our time with the Grade 2s, requiring a facilitator or student to gently pull on the zip tie to un-jam it temporarily. When troubleshooting this and other technical issues, Sonny said that he became comfortable over time as he gained experience with the kit's components and materials. Anita, on the other hand, reported that she didn't have to do much troubleshooting at all with the Grade 6s, since they were self-sufficient when problem solving.

VII. Conclusion

We presented a Paper Animatronics Kit aimed at elementary-aged students along with a user study in a K-6 lab school to validate its suitability in a classroom context. Our results indicate that the kit was effective at engaging students in the creative process, and provided opportunities for cross-curricular integration of STEM and literacy. Additionally, the Grade 2 teacher from our study expressed interest in offering students the choice to use animatronics in their upcoming science unit. We believe that the interdisciplinary nature of animatronics provides an effective way of bridging creative and technical activities by providing multiple entry-points for varying student interests. Incorporating cross-grade mentoring gave students motivation and inspiration to tell stories, fostered collaboration and idea-sharing, and encouraged self-reflection of prior learning.

We are interested in improving the interfaces and functionality of the boards in our kit, for example being able to program motions with the Knob Board would give students more control. Additionally, more investigation is needed into the state of creative and design thinking skills in STEM education to uncover how best to develop and scaffold these skills across the curriculum.

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