StoryMakAR: Bringing Stories to Life with an Augmented Reality & Physical Prototyping Toolkit for Youth

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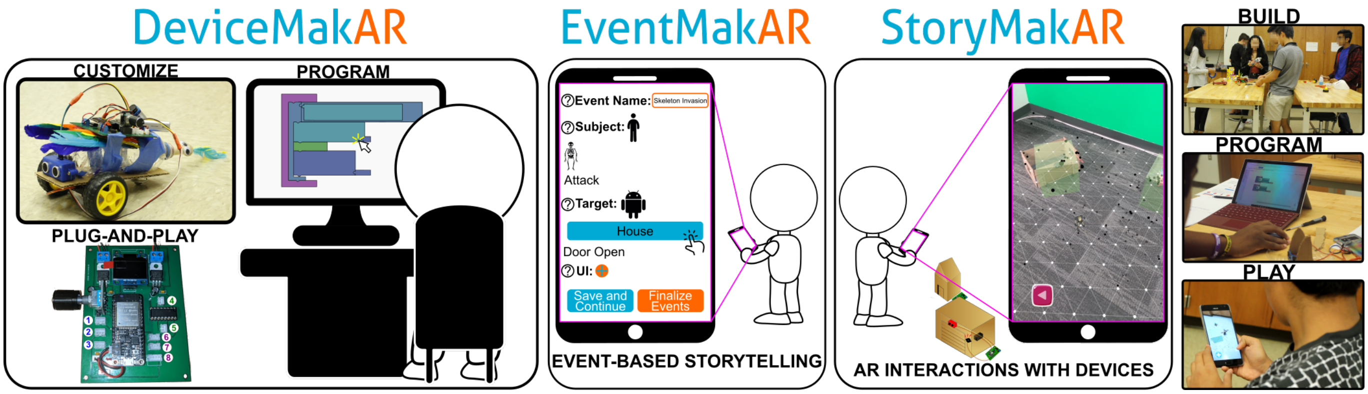

Figure 1: Overview of StoryMakAR workflow (from left to right). (a) Users build electro-mechanical devices, program them using our drag-and-drop environment, DeviceMakAR, and control them with our plug-and-play MakAR Board. (b) Users create events for their story with EventMakAR. (c) Finally, using an AR-enabled cell phone, users control the physical devices by using the virtual characters to create Virtual-Physical Interactions.

ABSTRACT

Makerspaces can support educational experiences in prototyping for children. Storytelling platforms enable high levels of creativity and expression, but have high barriers of entry. We introduce StoryMakAR, which combines making and storytelling. StoryMakAR is a new AR-IoT system for children that uses block programming, physical prototyping, and event-based storytelling to bring stories to life. We reduce the barriers to entry for youth (Age=14-18) by designing an accessible, plug-and-play system through merging both electro-mechanical devices and virtual characters to create stories. We describe our initial design process, the evolution and workflow of StoryMakAR, and results from multiple single-session workshops with 33 high school students. Our preliminary studies led us to understand what students want to make. We provide evidence of how students both engage and have difficulties with maker-based storytelling. We also discuss the potential for StoryMakAR to be used as a learning environment for classrooms and younger students.

Author Keywords

Maker Culture; Storytelling; Augmented Reality; Children

CCS Concepts

•**Human-centered computing** → **User interface toolkits;**

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INTRODUCTION

Storytelling is often thought of as the process of creating and/or engaging in narrative structures [25]. Today, storytelling is a tool used in a myriad of applications such as Education, Engineering, and Design. In fact, storytelling can be a powerful tool for building skills in communication, collaboration, creativity, and retention [70].

Researchers have established a connection between storytelling and making in an attempt to help expose people to technology in new and exciting ways. There are several different storytelling platforms that are intertwined with current trends in technology, including educational platforms like FaTe2 [24], interactive platforms like StoryRooms [3] and StoryMat [11], tangible platforms like StoryBox [65], collaborative platforms like TinkRBook [13], and highly creative robotics kits like Goldiblox [26] and Handimate [71, 58]. Add this to the mainstreaming of Augmented Reality (AR), which has ushered a brand new generation of mobile User Interfaces (UI) that transform our mobile devices into a gateway between the physical and virtual worlds.

Existing research has focused on using AR to bring virtual content into the real world in order to create exciting and unique experiences for young users [23, 37]; however, there is little research that transcends this idea by giving these users the power to augment and control physical objects that youth create, with virtual content. This paper presents StoryMakAR, an AR-IoT storytelling toolkit that combines physical construction, electronics, and an AR environment designed to merge physical and virtual content into a unique, storytelling experience. Using StoryMakAR, users can construct pre-designed physical devices with the provided hardware toolkit (e.g. house, car, garage, etc.) or design their own. Then, users connect their electronics to our custom printed circuit board (PCB) and program those devices using a drag-and-drop block programming interface. After all their devices are programmed, users can decide how they want to control the content and create new events for their story. Finally, users wirelessly pair their physical devices to an AR-enabled cell phone and bring their story to life through virtual-physical interactions. We offer three main contributions with StoryMakAR:

1. Design rationale extracted from preliminary studies that show how children engage in maker-based storytelling, what they make, and the issues that arise as a result,
2. The StoryMakAR system, which includes plug-and-play electronics, an AR-enabled app that helps users create dynamic storytelling environments, as well as two accompanying environments, DeviceMakAR and EventMakAR, which allow users to program their own customized devices and design the interactions between virtual and physical content,
3. The study and evaluation results of our system, which show that it can be used to easily create new and unique storytelling experiences.

RELATED WORK

StoryMakAR builds on prior work that utilizes technology designed for storytelling, AR interaction methods, kits that make assembling structures easy, and electronics toolkits for makers. Each of these areas is reviewed below.

Storytelling Technology

Storytelling platforms, such as Wonderscope [33], ARFacade [18], and Magic Cube [72], leverage the fact that AR transforms the device into a world-altering lens that not only allows the user to see into the virtual world, but to augment the physical world as well. Thus, this level of interaction and engagement provides a natural progression to use storytelling as a use-case for new AR technology. Early research in this area has shown that visual tag recognition systems are adept at augmenting specific objects [56], which can be used for storytelling [3]. Others use computer vision algorithms to create custom characters with paper, markers, and scissors, and play them back while being rendered on a new background [7] and animation tactics to show virtual characters performing animations based on user movement [17].

Some AR storytelling applications use a Head-Mounted Display (HMD) to show the user an augmented view of a prewritten story [35] and to show the user an augmented view of a story that progresses as they create various permutations of a foldable cube [72]. Others create an immersive environment where users interact with virtual characters through typed keyboard input [18], or to allow the user to directly author and interact with the virtual story content [8].

Other researchers have designed collaborative and tangible storytelling platforms that engage several users simultaneously in creating/authoring stories [62]. For example, Mobile Stories is a mobile application that facilitates creation of stories on multiple devices [19, 20]. ShadowStory takes the shadow puppetry artform and transforms it into a creative, technology-driven performance where students create their own stories, characters, props, and backdrops [43]. Meanwhile, RoboStory aims to enable users to create and present their own, original story in collaboration with others using a mixed reality tabletop storytelling support system [47, 46]. We build on this prior work by examining how high school students use StoryMakAR to collaborate and engage with the design of their own, original stories by writing, and by designing the interactions between the AR (virtual) content and their physical devices.

	Physical	Virtual
Physical	**Physical-Physical** Handimate [71] Topobo [54] Blynk [10]	**Physical-Virtual** —
Virtual	**Virtual-Physical** ProtoAR [50] TUIs for AR [31] Project Zanzibar [64] MotionBeam [67] HideOut [68] ConductAR [49] AR Prototyping [61, 60]	**Virtual-Virtual** Scratch [44] MyStoryMaker [45] Pokemon GO^{TM} [51]

Table 1: Interaction methods explored by StoryMakAR.

Interaction Methods

Through computer vision and spatial recognition algorithms, AR apps can create new interaction experiences with virtual and physical content and even users themselves through an HMD or mobile phone. The virtual characters that are used with StoryMakAR help provide immersive storytelling experiences. For our study, we focus on three interaction methods. *Physical-Physical Interactions* require users to physically manipulate a device through a physical controller (e.g. Joystick, cell phone screen, keyboard, etc.) and/or sensors. *Virtual-Virtual Interactions* allow users to have their virtual characters and other content interact with one another. *Virtual-Physical Interactions* enable AR systems to have virtual content interact with and control the systems physical content, while *Physical-Virtual Interactions* allow physical devices to control the actions of virtual content(see Table 1).

The interplay with physical devices differentiates StoryMakAR from the platforms in Table 1. The central focus of our StoryMakAR construction kit is the capability of incorporating electro-mechanical devices into a story to impart a sense of ownership of the users creations, and to make the entire story-making process as engaging as possible for the user.

Electro-Mechanical Construction Kits

The combination of mechanics, electronics, and programming creates a space that is difficult for someone without prior knowledge to be successful in. Construction kits provide a platform for users to plan, design and build structural models given a limited set of instructions. They are widely popular because of their simple assembly techniques and the satisfaction one receives from having completed a fully functional project (see LEGO Mindstorms [28], Nintendo Labo [52], and HandiMate [71, 58]).

Modern electronics toolkits are designed with the intention of reducing the learning curve for the layperson. Many toolkits introduce the idea of an electronic building block [41, 32], which provide error- and hassle-free ways of assembling electronics where the modules can be stacked magnetically without the need for any prior electronics experience. What is more, these toolkits are beginning to explore compatibility with construction kits like LEGO [27], microprocessor units [4, 48, 55], and even some more advanced Computer Aided Design/Manufacturing platforms. Enabling their usage can lead to unlimited possibilities in open-source projects (see Plain2Fun [66], Craftec [34], and MakerWear [38]).

Many of these kits afford their users an interface which allows them to logically or programmatically control their constructed devices by using the idea of block-based programming as a basis (similar to Scratch and Scratch Jr. [44, 22]). MakerArcade [59] is one such system that uses two similar programming environments, which were built with Google's Blockly [42], to help children program their electronics, as well as the arcade games that they design. Since Blockly is open-source, many other block-based programming tools exist, including ArduBlockly and BlocklyDuino [6, 9], which enable the programming of microcontrollers, BlockyTalky [16], which creates a network of mobile devices and musical instruments, and code [dot] org [36], which is a site filled with tutorials, posters, and other content to help students learn the fundamentals of programming. StoryBlocks [40] takes the idea of block-based programming even further with its tangible blocks to help visually impaired students create accessible stories.

StoryMakAR separates itself from these other platforms and toolkits because of its integration of these areas. StoryMakAR is not only a lens into the virtual world, but provides a different perspective on virtual-physical interaction by transforming AR content into something with which a physical device can communicate and create new experiences for children.

MOTIVATION & DESIGN GOALS

To design and develop the StoryMakAR system, we took an iterative design-based research approach [73]. We first conducted three preliminary Storytelling Challenges, where the participants were placed in groups of four at random and asked to write their own, original short stories. The participants were primarily novices in the areas of electronics and design. Using the information from this preliminary study, we elicited critical design criteria for the StoryMakAR system. We then conducted pilot studies with our initial system prototype with participants who had experience with using AR applications, or experience with construction kits before deploying our final prototype of the system. In this section, we describe the Storytelling Challenge and the resulting design goals.

Scouting an Approach to StoryMakAR

In order to gather and curate our design criteria for StoryMakAR, we conducted three workshops with young students (ages 12-18). We created a Storytelling Challenge wherein students collaboratively wrote a story, designed and built characters, props, and other objects, and then presented their story to the rest of the teams in that group. In total, we had 53 students participate in the study. 26 students had experience with electronics before this workshop and 40 students had at least "a little" engineering experience.

Participants were given a storytelling manual to complete, based on works from leading developmental psychologists and story structure experts, including Stein [63] and Fitzgerald [21]. The storytelling manual was of a workbook style, which gave participants space to write the setting, theme, and conflict of their story, storyboard the different parts of their story (Introduction, Rising Action, Climax, Falling Action, and Ending), *and* write the corresponding narrative text. Participants crafted items with recyclable/reusable materials like cardboard, plastic bottles, and aluminum cans. These items were embedded with electronics and used to animate their stories. Since our participants were mostly inexperienced in electronics, they only used basic electronic components (LEDs, DC motors, and electric switches). Once completed, the participants shared their stories with other groups.

Among the 53 participants, there were 16 automotive objects (drives around with wheels), 8 actuating objects (stationary and moves less than 360 degrees), 17 sensory objects (using light or sound modules), 12 rotary objects (motors rotate freely), and 18 stationary objects (no electronics), yielding 71 total crafted objects. Through our survey analysis, participants were asked *What did you enjoy about the Storytelling Challenge?*. They were given several answer choices regarding different aspects of the Challenge, where the choices we deemed as highly hands-on (building electronics, crafting objects, working in teams, etc.) were chosen more than others which weren't as hands-on (writing/narrating/presenting the story). Creating characters and devices that perform animations were among the top two choices when asked what they would expect a storytelling software to do, and plug-and-play electronics was the top choice when asked what they would expect to come with a hardware toolkit to accompany a storytelling software. Students made just as many story devices with simple LED circuits or no electronics at all (total=35) as they did devices with more complex circuits with motors (total=36). In general, we like that the students were exhibiting multiple inroads to creating their devices. For instance, four teams wanted to start with the electronics first and build the hardware around that, while others tend to add electronics as they are building the hardware and come up with new ideas.

System Design Goals

Informed by these preliminary studies, our own experiences with Storytelling software [44, 39] and relevant prior work [57, 67], we synthesized the following design goals:

- **Accessible:** Accessible: Previous toolkits, such as those mentioned in the Related Work section use high fidelity materials and are costly. In contrast, we put an emphasis on mixing input and output (I/O) devices with low fidelity (lo-fi) materials to increase accessibility.

- **Engagement:** StoryMaKAR should engage the user throughout the play cycle (Design–Build–Play) by encouraging them to explore new configurations when they've finished with older versions [30]. StoryMakAR provides tools to encourage iterations among users.

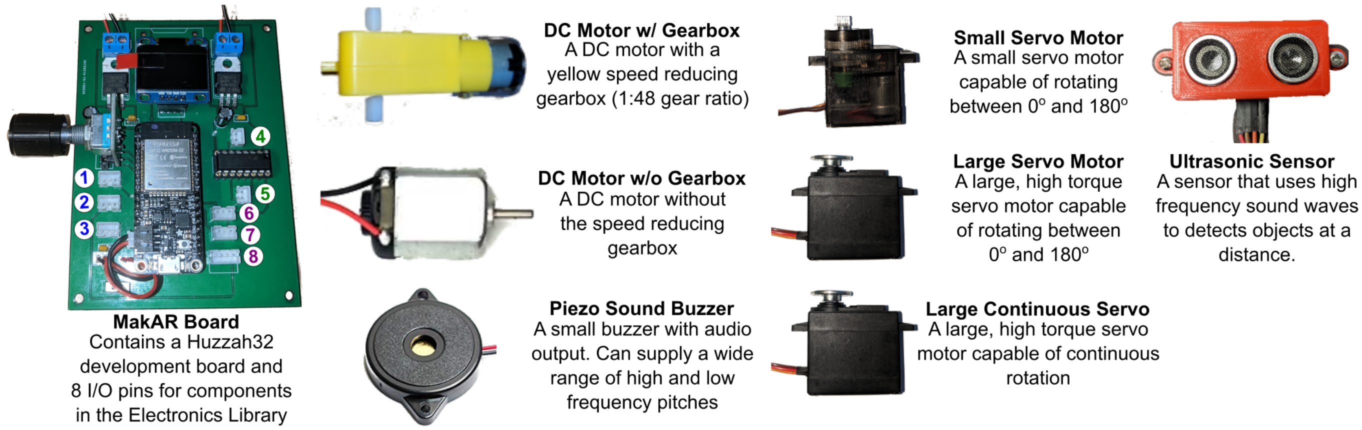

Figure 2: Our Electronics Library, which consists of our custom designed MakAR Board (left) and seven electronics modules: 2 DC motors, 3 servo motors, 1 sound buzzer, and 1 sensor

- **Expressive:** StoryMakAR gives users control over their storytelling experience by altering the existing physical content, or by creating their own,
- **Plug-and-Play:** Users should have electronics that are ready for play with minimal configuration [12, 5],
- **Low Floors, Wide Walls:** Borrowing from Resnick and Silverman [57], StoryMakAR should be accessible to children of various skill-sets by eliminating the need for prior electronics and programming knowledge.

THE STORYMAKAR SYSTEM

Based on the design goals described in the previous section, we designed StoryMakAR, a plug-and-play hardware platform with an integrated AR environment that brings stories to life. The StoryMakAR system is composed of (1) an electronics toolkit that includes a microcontroller hub device that connects to and dynamically controls various I/O devices, (2) a block-based programming web application for programming Arduino [4], [1] called DeviceMakAR, (3) an event planning application called EventMakAR to help students design the interactions between their virtual and physical content, (4) a cell-phone application called StoryMakAR that wirelessly pairs to the electronic devices and turns them into Internet of Things (IoT) devices, and (5) a structure toolkit designed to help users quickly and easily assemble story elements.

Electronics Toolkit

The electronics that accompany the structure toolkit are modular by design and include a main device, and several, smaller sub-devices. We found that many off-the-shelf toolkits are hard for novices to learn. Based on our design goals, we designed a **plug-and-play** PCB that we call the MakAR Board. In order to deliver a maker-based storytelling experience, our PCB was required to include a microcontroller unit (MCU), several functional components for I/O, and a power source to power it all. We selected a Huzzah32 ESP32 Feather Board [1] because of its small size, Bluetooth Low Energy (BLE) and WiFi capabilities, and its numerous in/out pins. Additionally, a small group of off-the-shelf electrical components, which are common to many maker-based projects were selected when designing the electronics toolkit (see Figure 2).

We designed the MakAR Board to be plug-and-play; users should not be required to undergo a significant amount of training in order to connect their sub-devices to the main device (Figure 2). The MakAR Board gives the user access to 8 I/O ports. Ports 1–5 are reserved for sub-devices that receive output commands, while ports 6–8 are reserved for sub-devices that provide input information. Sub-devices with two, three, and four pins can be used with this board (Figure 2). Once the MakAR Board is connected to WiFi, users can assign the Board a device type and select the occupied pins.

DeviceMakAR

DeviceMakAR is a graphical programming interface that allows the user to plug code blocks, operators, and values in various combinations to create Arduino code and outputs syntactically correct code in the Arduino programming language. Built from the open-source web app BlocklyDuino [9], DeviceMakAR builds on top of, and extends to the ESP32 libraries, which we are using for our electronics. Users can create their own functions based on the electrical components they select from our Component Library. DeviceMakAR makes use of common Arduino commands such as `DigitalWrite()` and `DigitalRead()`, while allowing users to choose from a list of our own built-in commands. Each device is programmed individually in DeviceMakAR, compiled, and uploaded to the MakAR Board via an Over-The-Air (OTA) server.

EventMakAR

EventMakAR is an interface that allows the user to design the interactions that happen between their virtual characters and physical devices (see Figure 3). Each event has (1) an *Event Name*, describing what is happening in the event, (2) a *Subject*, which is the **character** or **device** that the user controls. Users can choose between any of our four characters, or from a list of devices. If a virtual character is chosen, users can select an animation for the character to perform during the interaction. If a physical device is chosen, the list of functions that they programmed will be available for them to select. (3) a *Target*, which is the **character** or **device** that performs an action when the subject interacts with it. Users can choose between the virtual characters or physical devices for these interaction, and (4) a *User Interface*, which gives the user control over their subject during that particular event.

StoryMakAR creates Virtual-Physical Interactions by allowing the virtual content to come into contact with the physical content, creating physical actions in the real world. DeviceMakAR gives students a quick and simple way to program their devices without the need to learn the details of the Arduino programming language and environment. Lastly, EventMakAR gives users control over the story flow, and the design of their interactions. This ecosystem is what sets StoryMakAR apart from all other AR platforms and storytelling toolkits.

Structure Toolkit

StoryMakAR's structure toolkit was designed to provide the user with the physical devices to be used in their stories. The toolkit consists of (1) a *House*, intended to respond to a virtual character walking up to it by moving a small servo to open the door, (2) a *Car* to work standalone where the user can drive the car for their story, or work alongside (3) the *Garage* to open the garage door, where the user can move a physical device into the range of the ultrasonic sensor and rotate the door open (see supplementary video). The design of these devices were chosen as a starting point for our kit because of their relation with each other. These elements also showcase the two different interaction methods that use physical devices. Additionally, we provide our users with a myriad of recyclable materials, 3D printed parts, connectors, fabric, paint, and many other items that they can use to customize their creations.

PILOT STUDY: INITIAL STORYMAKAR PROTOTYPE

Our initial exploration of StoryMakAR was to gain an understanding of how users interacted with a software/hardware system like this, and what features they would expect from it. We conducted pilot studies with our initial version of StoryMakAR, which did *not* include the use of DeviceMakAR and EventMakAR, and used the first prototype of our MakAR board. Our findings were used to improve our final system design, as well as our workshop design.

Comparative Study

We designed a within-subjects study to detect differences between StoryMakAR and another storytelling platform, Wonderscope [33]. We chose Wonderscope for comparison because it gives users an engaging experience by choosing from a list of pre-written stories and providing voice input to the system as a method of interacting with characters and progressing through the story. Additionally, we aimed to test our event-based storytelling method with a more traditional storytelling method. We tested our hypothesis that virtual-physical interactions created through the manipulation of both virtual *and* physical content simultaneously is more engaging in StoryMakAR than the interactions in Wonderscope. To better assess the effects of maker-based storytelling, we selected participants based on one of two criteria: participants must have experience using (1) any AR application *or* (2) any electromechanical construction kit. We chose these criteria to gain a better perspective about the usability of the StoryMaKAR structure and electronics toolkit, as well as the AR app from our users. In total, we had 10 users (8 male, 2 female) between the ages of 18-35 years from engineering fields to participate in our user study. Eight users had previous experience with AR applications and six of them had played with construction kits before. None of our participants had been previously exposed to Wonderscope or StoryMakAR. Participants were given $10 compensation for taking part in our user study.

All participants were introduced to (i) the AR application, Wonderscope, at the beginning of the session to ensure that they were familiar with key AR interaction methods for storytelling. They were then introduced to (ii) the structure toolkit and asked to construct each of the devices, followed by (iii) the electronics toolkit for connecting all of their devices, and finally (iv) the StoryMakAR app for creating their stories before they (v) narrated their own stories. Users began by playing through the default story called *Wonder's Land: Ringmaster Wanted* where the main character, Wonder, needs the users help getting everyone to the carnival on time. Due to time constraints, we required the users to complete only the first 3 chapters of the default story.

The study lasted for approximately 2 hours for each user. Users were also asked to fill up a survey in the form of a questionnaire at the end of each part of the user study. One of the researchers took observational field notes, which were analyzed and used to help interpret the results from our survey data.

Results

In this section, we report all Likert Scale questions with mean (M), median (m), and standard deviation (σ). Though the participants were limited by time, participants explored the various interaction methods and other features of StoryMakAR after completing the introduction in part IV. Participants were able to write and verbally narrate a wide range of stories based on our default events, such as *The Great Barbarian Heist* and *Attack of the Space Skeleton*. One user went as far as to enthusiastically say *"I want to use everything that I can"* when asked to begin part V. Other participants stated that they liked the house due to the virtual-physical interactions. Additionally, we found the MakAR Board was also a determining factor in motivating users to explore different devices and **easily** bring their stories to life (M=4.90, m=5, σ=0.3). In fact, two participants stated that they were worried about the electronics due to their lack of knowledge about the field, but were pleased that the electronics were simple enough for them to use effectively.

Some challenges that users faced included difficulty assembling devices (following instructions in our manual), using the phone screen as a controller (as opposed to a physical button/joystick), and some technical difficulties (e.g. incorrect pairing between phone and MakAR board). The learning curve for incorporating these devices was significantly reduced to allow the participants to focus more on the story and interactions, and spend less time designing the circuits and the device itself. When asked which was more engaging between Wonderscope and StoryMakAR, nine users chose StoryMakAR, stating that it was due to the merging of physical and virtual content, the lack of external knowledge about circuits and programming necessary to use StoryMakAR, and the "fun" and "entertaining" elements of creating your own story. One participant went as far as to say, *"[The] StoryMakAR System allowed you to use physical reality to interact with virtual reality which gave the user something tangible to see and adds an extra fun factor to the experience."*

Outcomes

This experience also informed us of some key modifications that we needed to make to the StoryMakAR system: (i) add a

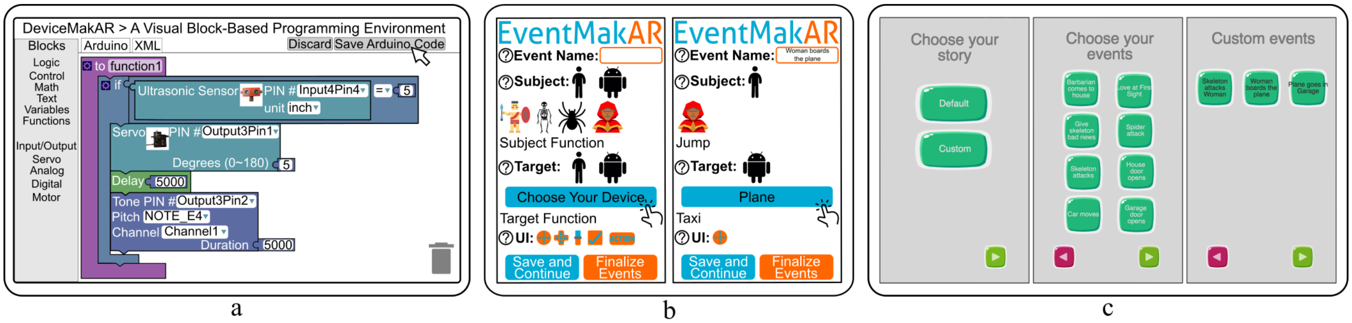

Figure 3: After our users design and build their devices, they can use (a) DeviceMakAR to program them and (b) EventMakAR to create the event for their story. Users can choose our default events or their own custom events in (c) StoryMakAR. See supplementary video.

screen to the MakAR board to make the set-up process simpler and more robust, (ii) to add functionality of EventMakAR and DeviceMakAR to provide users with lo-fi materials to help them program and integrate their own custom devices into their stories, and (iii) add two new sub-devices, including the sound module and the DC motor without a gearbox, as well as a new female character for them to choose from to encourage greater diversity in device design and story creation.

STUDY 1: DEFAULT EVENTS & DEVICES

After the initial refinement of the StoryMakAR system and restructuring our user study protocol, we ran a workshop at the University with a group of high school students (N=14; ages 14-18). During this workshop, we were focused on similar goals as in our pilot study; we observed the *usability* of our system while examining *how* the students interact with StoryMakAR and *what* features they expect to see without having the ability to design and program their own devices. Through these observations, we aimed to answer the following research questions:

- How do virtual-physical interactions influence the student's approach to storytelling and story-making?
- How does a system that combines structural and electrical components with AR contribute to a design space for virtual-physical interactions?

We returned to our initial target age group in order to study age related differences in the use of StoryMakAR. Lastly, we used the results from this study to design our custom events and devices workshops, which are described in the next section.

Recruitment Method

High school students were recruited from a group that was attending a 2-week *Smart Toys and Robots* class as a part of a summer camp run at the University. The workshop was free for the students that were taking the class. We had fourteen participants (2 female, 12 male) in the workshop. Participant demographics can be found in Table 2.

Study Procedure

Since this group was younger than the group in our pilot study, we prepared a different set of plans for this workshop, giving the students more time to complete the tasks and be creative. The workshop lasted 3 hours and included: a pre-study survey, an introduction to the StoryMakAR Structure Toolkit (45 minutes), Electronics Toolkit (15 minutes), and the StoryMakAR app (15 minutes). Once they were familiar with the app and workflow, we gave the students 60 minutes to write a short story based around the given story elements and characters, 30 minutes to present their stories to the group (˜ 5 minutes per group with 2-3 minutes between groups for set up), ending with a post-survey (15 minutes). The students were broken into 4 teams (two teams of 3 students; two teams of 4 students) and allowed to collaborate with their teammates to create a fun and interactive story. Finally, each team was paired with an adult from our research group to facilitate creativity and to keep them on track.

Writing and Presenting the Story

After the students completed the introductory phase of the study (first 1.25 hours), they began to write their stories. Using an updated version of the storytelling manual from our preliminary studies, the students ideated their story structure. We gave options to the students for how they wanted to "write" their stories. They could either (1) sketch their stories into storyboards and include annotations for narrating, or (2) write out their stories in English. We found that each group preferred to sketch and storyboard as opposed to writing their story. Each team was given up to 5 minutes to present their story. The StoryMakAR cell phones were attached to a screen so multiple people could view the story at the same time.

Data and Analysis

We used a mixture of qualitative and quantitative data to assess our two research questions. We analyzed content from the storytelling manual, observational field notes taken by one of the researchers, and the pre- and post-survey data. The pre-survey gathered information about the participants, including demographics and prior relevant experience with storytelling software, electronics, phone-based AR applications, etc. The post survey asked questions about how the participants felt about

Grp Size	Gender		Elec Exp		Engr Exp					AR Exp	
	B	G	Y	N	G	L1	M	L2	N	Y	N
4	4	0	3	1	0	0	2	1	1	0	4
3	3	0	2	1	1	1	1	0	0	3	0
4	4	0	4	0	0	1	1	2	0	1	3
3	1	2	2	1	0	2	0	1	0	1	2

Table 2: User Study 1 workshop group sizes, demographics, and student experience levels taken from our User Study 1 pre-study survey where Gender (B-Boys, G-Girls); Elec Exp (Y-Yes, N-No); Engr Exp (G-A Great Deal, L1-A Lot, M-A Moderate Amount, L2-A Little, N-None); AR Exp (Y-Yes, N-No).

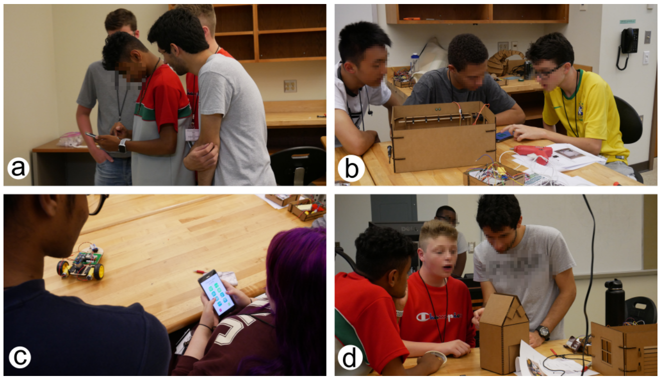

Figure 4: Participants (a) engaging with researchers and (b) collaborating to build physical devices for (c) their chosen story events, and (d) creating experiences they have never seen before

StoryMakAR and their stories, collaborating with others to tell stories, the different interaction methods, and other aspects of StoryMakAR. Both surveys used a mixture of closed-ended Likert scale questions [29] and free response questions (e.g. *What, if anything, did you enjoy about writing your stories and presenting to your friends?* and *If I could add any functionality to the StoryMakAR software, I would add...?*).

Results

In this section, we discuss our key themes from Study 1 and some common occurrences amongst participants related to using the StoryMakAR app, structure toolkit, and electronics toolkit. We report all names as pseudonyms with (gender) and all Likert Scale questions are reported with mean (M), median (m), and standard deviation (σ).

Presentations

Throughout the workshop, students were engaged in the storymaking process. During the presentations, the researchers noted how many of each interaction type were present in the stories. Below is a summary from a story written by students.

The story takes place on a sunny summer afternoon. Billy the Barbarian is the main character. One day, it started to rain while Billy was driving home, but Billy's car wasn't designed to drive in the rain. Billy pulled over, but ran into a spider on the side of the road. The spider attacked him! Billy fought back and roundhouse kicked the spider until he surrendered. After the rain cleared, Billy was able to drive home. He parked his car in the garage and went inside his house.

Overall Reactions

In their post-study survey, all but one student reported having fun while constructing the devices (M=4.71, m=5, σ=0.59). Likewise, 11 students reported that the easily connecting electronics helped them quickly bring the physical structures to life (M=4.07, m=4, σ=0.70). The majority of students reported that they enjoyed creating Virtual-Physical interactions (M=4.14, m=4, σ=0.83), Virtual-Virtual interactions (M=4.07, m=4, σ=0.80), and Physical-Physical interactions (M=4.14, m=4, σ=0.74). Finally, several students reported that they would like to have more physical devices (M=4.43, m=5, σ=0.73) and virtual characters (M=4.21, m=5, σ=1.15) for their stories. When asked if there was anything that they enjoyed about writing and presenting their stories, *imagination and creativity* (N=4) were mentioned the most because *"it feels good to lead the storymaking and create a story only limited to our imagination"* (Leo, Male), and *"we got to be creative and build things"* (John, Male). *Collaboration* (N=3) and *Fun* (N=2) were also mentioned by students because *"The reactions of my peers were fun to watch"* (Sara, Female) and they were *"laughing and making the story a little more exciting"* (Joran, Male).

Summary

In conclusion, the results of Study 1 showed that the students were engaged throughout the storytelling process and were able to come up with original stories with various types of interactions. Virtual-Physical interactions were a key part of their engagement as indicated by the high mean and low standard deviation from the survey. However, one constraint from the study was the customizability of the devices since the participants were limited to only the house, car, and garage. Although the students were not able to create their own devices, they were able to add enhancements to the devices by adding paint, feathers, and other materials found in the classroom.

STUDY 2: CUSTOM EVENTS & DEVICES

In order to gain insight into the capabilities of maker-based storytelling for high school students, we conducted six three-hour workshops with several groups of students at the University (N=19; ages 14-18). This study aimed to answer the following research questions:

- In what ways do StoryMakAR, DeviceMakAR, and EventMakAR serve as a design space for high school students to create their own interactions?
- *What* are the students making within this design space?

We collected both qualitative and quantitative data to assess our two research questions. We analyzed content from the storytelling manual, observational field notes taken by one of the researchers, and the post-study survey data.

Recruitment Method & Study Procedure

Students were recruited via word of mouth and postings on our social media pages. Informed consent regarding the study was received from both parents and students. The students were split up into groups based on the number of students present during the day of the workshop. We had 19 participants total (10 male, 9 female) across six total workshops. Each student received $10 compensation, as well as lunch for participating in the study. See Table 3 for participant demographics.

Grp Size	Gender		Elec Exp		Engr Exp					AR Exp		Prgmng Exp	
	B	G	Y	N	G	L1	M	L2	N	Y	N	Y	N
4	1	3	4	0	0	1	1	2	0	2	2	4	0
3	1	2	1	2	0	0	2	1	0	3	0	3	0
3	2	1	3	0	0	0	1	2	0	1	2	2	1
1	1	0	1	0	0	0	1	0	0	0	1	1	0
1	1	0	1	0	0	0	1	0	0	0	0	1	0
7	4	3	4	3	0	1	0	3	3	5	2	4	3

Table 3: User Study 2 workshop group sizes, demographics, and student experience levels taken from our User Study 2 post-study survey where Gender (B-Boys, G-Girls); Elec Exp (Y-Yes, N-No); Engr Exp (G-A Great Deal, L1-A Lot, M-A Moderate Amount, L2-A Little, N-None); AR Exp (Y-Yes, N-No); Prgmng Exp (Y-Yes, N-No).

Each session lasted ˜3 hours and followed a different format than User Study 1. The study included: a 30 minute introduction to StoryMakAR, a 30 minute introduction to DeviceMakAR and EventMakAR, 30 minutes for writing their story, 1 hour for designing, building and programming custom devices, 20 minutes for creating events and playing their story, and 10 minutes for the post-study survey. Similar to Study 1, students were broken into teams based on the number present at the workshop. We had two groups of 1, two groups of 2, three groups of 3, and one group of 4. Lastly, each team was paired with an adult from our research group to facilitate creativity and to keep them on track.

Designing Physical Devices

From our previous studies, we noted that students much preferred drawing/storyboarding to writing text for their story; however, some students used the writing space to jot down notes about their story, physical devices and characters. Additionally, we noticed some issues for students who wanted to visualize their events by using the storytelling manual. Students were putting a lot of effort into storyboarding, using their imagination to come up with very detailed drawings. But, in doing so, students would lose time to actually play with and explore StoryMakAR. Given all of the feedback, we updated the storytelling manual with space to draw their custom devices, and choose the different parts of their story by following an EventMakAR template. We found that by providing this storytelling manual, students were more productive and focused more on the task of designing and programming their devices with DeviceMakAR, and designing the interactions that they want for their story with EventMakAR.

Programming with DeviceMakAR

All but four students had prior experience with programming, coding, and scripting in general. Nonetheless, each group was able to successfully build and program their device with DeviceMakAR. After creating the blocks for their functions, the researchers showed participants the auto-generated Arduino code. Several students were impressed and excited about this feature, and showed their excitement through affirmative facial expressions and exclamations such as "Wow!" and "Cool!" We found that students were more likely to use the larger blocks with our built-in functions (e.g., Servo block and Motor block) as opposed to designing their own large functions with the `digitalWrite()` and `digitalRead()` blocks. This is in spite of some students (N=7) having prior experience using an Arduino. We also noticed that only a single group explored the use of logic statements and loops while using DeviceMakAR. We attribute this to the lack of sensors that we included in our electronics library since several students expressed their interest in using a wider array of sensors such as color sensors, line followers, etc. Future versions of our electronics library will include a better integration of sensors.

Interaction Design with EventMakAR

After being introduced to EventMakAR, the researchers observed the students having a relatively easy time creating events for their story. Despite the ease of use, students still wanted to add some functionality/features to the system, including a way to create physical-virtual interactions (as opposed to just virtual-physical interactions) where a physical device (subject) could cause a virtual character (target) to perform some action. Future versions of our system will include functionality such as this to create even more diverse storytelling experiences.

Results

Below, we present our results from the Custom Events and Devices workshop: (1) what the students designed and built for their stories, and (2) key differences in student engagement and enjoyment among the different group sizes.

Diversity of Stories & Devices

In contrast to the stories that were written by the students in Study 1, the custom events and devices (Figure 5) gave us insights to the kind of devices students were interested in designing for their story. In order to analyze our results, we focused on the characters and devices that each group assigned to be the subject and target of each event, what interaction methods they invoked, and the number of events they decided to have for their story. Table 4 shows a breakdown of events that students made.

Overall, the students created 11 custom devices, and 8 of them can be categorized into the five device types from our Storytelling Challenge: Stationary (1 device), Actuating (3), Sensory (0), Rotary (3), and Automotive (1). Two of the custom devices were hybrids of more than one device type: Automotive + Rotary (Bi-Plane) and Automotive + Sensory (Thomas the Tank). Lastly, one group wanted to modify our pre-designed car by fastening their character *Yarnboy* on top of it (see Figure 5) for all devices). From our electronics library students were interested in using the following electronics: DC Motor without gearbox (5), DC Motor with gearbox (2), MG996R Servo (1), FeeTech FS5103R Continuous Rotation Servo (5), Sound Module (1), and Ultrasonic Sensor (1).

Consistent with our preliminary Storytelling Challenge, students displayed several different inroads while designing their devices and writing their stories. In particular, Sean (Male) took a very methodical approach to building his *Bi-Plane* by making precise measurements with calipers and asking for input from the researchers about his device. A group consisting of Anna (Female), Max (Male), and Anthony (Male) took a similar approach, but also wanted to test their *Rubber Band Shooter (RBS)* and *Drawbridge* before performing their final story. Jane (Female) and Yvonne (Female) on the other hand needed some inspiration from web searches when deciding

Grp Size	Custom Device(s)	Events				
		#	V-P	V-V	P-P	None
2	Shariffy (Helicopter)	1	1	-	-	-
2	Plane	1	1	-	-	-
3	Helicopter	4	2	1	1	-
3	Drawbridge, RBS, Road Sign	3	1	-	2	-
1	Bi-Plane	3	-	1	2	-
1	Bird	5	-	5	-	-
3	Thomas (Tank)	5	2	-	1	2
4	Leon Muck (Car), Yarnboy (Car)	1	-	-	1	-

Table 4: Breakdown of custom devices, events, and interactions made by students during Study 2. The last column indicates events where students had only selected a subject and not a target (no interaction).

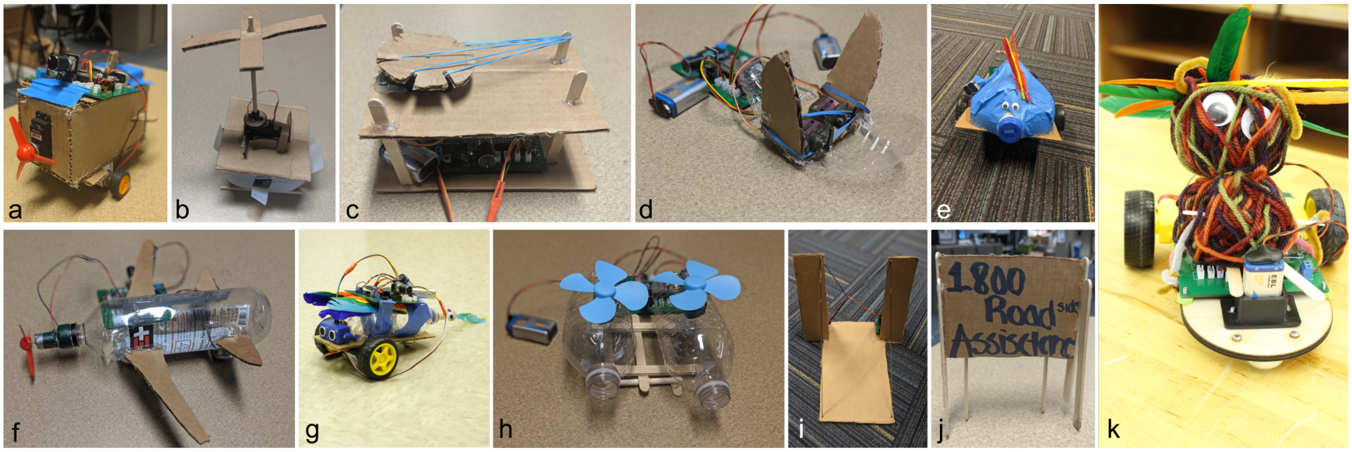

Figure 5: The custom devices made by students in User Study 2: (a) Bi-Plane, (b) Shariffy (Helicopter), (c) Rubber Band Shooter, (d) Bird, (e) Thomas the Tank, (f) Plane, (g) Leon Muck, (h) Helicopter, (i) Drawbridge, (j) Road Sign, (k) Yarnboy.

what type of device they wanted to create before they settled on their *Plane*. Lastly, the group consisting of Omar (Male), Jake (Male), Vanessa (Female) and Jasmine (Female) talked a lot about the backstory behind their two devices *Leon Muck* and *Yarnboy* and even developed some pseudocode before jumping in and programming with DeviceMakAR.

DeviceMakAR played an integral role in how the students designed their devices. The group consisting of Jimmy (Male), Naomi (Female), and Daniel (Male) wanted to use two continuous rotation servos for their wheels as opposed to the DC motors. Programming them was just as simple as programming the DC Motors since they could use our Servo block. Another example of the ease of use that DeviceMakAR provides is with the *Shariffy* helicopter that was made by Erika (Female) and Patrick (Male), which contained just a single continuous rotation servo. Lastly, Ben's (Male) *Bird* used two micro servos and was simple for him to program; however, he did run into some issues due to a lack of fidelity in the design of his device. We attribute this to him being the only student present at this workshop. Nonetheless, all of these examples elucidate the wide range of creative opportunities for students to design, build and program their own devices for stories. For more, see our supplementary video.

Student Engagement and Enjoyment

Among the varying group sizes, we analyzed some key differences in students' level of engagement as they were designing, building, and programming their devices, and while writing their stories. As we expected, the larger group sizes (3 and 4 students) were able to divvy up the work of building, decorating, and programming amongst the various members. This not only saved the students time during the study, but also gave them room for improvement and iteration. Max, and Anthony were very enthusiastic about testing their Rubber Band Shooter once they had finished crafting it and Anna was working on the drawbridge; however, they all were engaging in dialogue when writing their story. On the other hand, Kevin (Male), Gabrielle (Female), and Kayla (Female) decided to work together the entire time while discussing their story, building their *Helicopter*, and even passing the phone to each other while using EventMakAR and StoryMakAR.

Contrarily, groups with only 1 or 2 students struggled to complete everything in a timely manner. Although the groups of two could have split the work between them, both teams decided to stick together to complete all the tasks, just as Kevin, Gabrielle, and Kayla did. The difference here is that in the group of three, they were able to split up tasks for their device amongst the three of them; whereas, with a group of two, there was more work for fewer people. This also limited their use of lo-fi materials that the larger groups were able to take advantage of. As stated earlier, the quality of Ben's bird device suffered because he was by himself, which is why, after testing the bird and seeing it not function as he intended, he chose events that used only virtual characters rather than fixing his device. Despite all of these disadvantages, Ben stated that *"it was fun to show off the story that I created in my head,"* when asked what he enjoyed about writing and presenting his story.

Overall Reactions

In their post-study survey, all but one student reported that it was easy to connect their motors and sensors to the circuit board (M=4.37, m=4, σ=0.74) and are glad that they don't have to use knowledge of electronics to operate StoryMakAR (M=4.84, m=5, σ=0.36). When asked if they believe that the easily connecting electronics helped them quickly bring their physical structures to life, all but two students responded in the affirmative (M=4.26, m=5, σ=0.91). We received much more consistent scoring from the students in Study 2 when asked if they enjoyed creating Virtual-Physical interactions (M=4.68, m=5, σ=0.57), Virtual-Virtual interactions (M=4.68, m=5, σ=0.57), and Physical-Physical interactions (M=4.84, m=5, σ=0.36). Lastly, most students reported that using the blocks to program their devices was easy (M=4.16, m=4, σ=0.93). When asked if they could add any functionality to the StoryMakAR system, *Physical-Virtual Interactions* (N=4) and *"more characters"* (N=3) were common responses. We also asked the students what they enjoyed about creating their own events with EventMakAR, to which they responded *"There was a lot of freedom to incorporate different parts both physical and AR,"* (Jasmine, Female) *"It was a fun creative outlet,"* (Vanessa, Female), and *"I really liked how seamless and easily we could integrate the events."* (Anna, Female).

Summary
From Study 2, it is clear that the students enjoyed being able to design, build, and play with devices that they had full control over. With the large number of automotive devices that were used, it is important that our system provide as much support around that aspect of the system as possible. Additionally, students are more than capable of using StoryMakAR, EventMakAR, and DeviceMakAR as a space where they can design their devices, as well as the interactions between those devices. Our findings also show that, given more time, students can escalate the fidelity of their devices and design even more complex storytelling experiences.

DISCUSSION & FUTURE WORK
Our results show that students across our target range (ages 14-18) were able to successfully design, build, and program their own custom-made devices given a relatively short period of time, creating unique storytelling experiences. What is more, our findings prove that maker-based storytelling can enable users to utilize AR to its full potential. Moreover, StoryMakAR achieved this while integrating traditional interaction methods alongside the Virtual-Physical interaction methods that AR affords. In this section, we discuss future extensions and directions for evaluating StoryMakAR, and some limitations therein.

Future Extension & Limitations
Experimental connectors designed for prototyping physical structures (similar to Shape Structuralizer [14]) is being explored as a potential medium for **Enhancing the Structure Toolkit**. Additionally, we are developing a base structure that could be changed into several different physical devices by replacing certain parts. One of the features that many of our user study participants said that they would like to see added to the StoryMakAR app was **Voice Recognition**, which is a feature in Wonderscope and LightAnchors [2]. Rather than tapping through each event to change their interactions, users can set up keywords or phrases that the app could recognize and automatically switch to a different event. We also plan to explore other AR Interaction Methods, such as the direct manipulation technique from Portal-ble [53] and the physical-virtual interactions that were not explored in this study [69]. We also plan to **Expand the Electronics Library** to include a wider array of output modules such as LEDs and solenoids, as well as input modules like line followers, color sensors, pressure sensors, etc. Lastly, our research to date has focused on the usability and engagement of the system; however, there is potential for students to learn in both formal classroom settings, and informal extracurricular settings. We plan to **Evaluate StoryMakAR as a Learning Tool** for kids. We believe StoryMakAR has the potential to become a fully immersive and interactive system for youth to learn subjects like computational thinking and electronics [36, 15, 12, 5]. Intrinsic to the design of StoryMakAR, the one main limitation to StoryMakAR is its small scale story elements. Issues involving mapping drift with SLAM limit us to a small area that can be controlled for positioning error.

CONCLUSION
This paper presents a new AR platform, StoryMakAR, designed with Makers in mind. Additionally, we curated DeviceMakAR and EventMakAR with which students are able to program and integrate their own custom-made devices into a story written by them. We learned about the strengths and weaknesses of maker-based storytelling and how it can be used with AR to bring stories to life. We argue that control over the interactions between virtual and physical content affords the user a more direct and unique opportunity to engage that content and leverage the full strength of an AR-IoT platform like StoryMakAR. Through our design guidelines, we were able to create a system that reduces the barrier of entry for youth to design, build, and program electro-mechanical devices. Users also design the interactions with those devices and their virtual characters. We offer these general design guidelines for future platforms that merge physical prototyping, AR, and IoT.

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