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THE SYMBIOTICS SYSTEM: DESIGNING AN INTERNET OF THINGS PLATFORM FOR ELEMENTARY SCHOOL STUDENTS

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We describe a LEGO-compatible Internet of Things Technology (IoT) designed to enable elementary school students to learn about IoT by building their own smart, connected products. The Internet of Things is any network of physical devices that can share information over the internet. Using small, Wi-Fi enabled microprocessors, Grove sensors, digital fabrication tools, LEGO bricks, and the LabVIEW programming interface; an IoT system was designed specifically for use in elementary school classrooms. This design case details the barriers to entry that exist for using the Internet of Things with young students, the design decisions made to lower those barriers to entry, and the results of a pilot study conducted using the developed technology with second-grade students.

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CONTEXT

The Tufts University Center for Engineering Education and Outreach works with various industrial partners, such as LEGO Education and PTC, who are interested in exploring ways of lowering the barriers to teaching complex thinking skills to young students. As designers, we were interested in discovering if younger students could master some of the more complex thinking resulting from distributed, internet-connected, systems. We created a set of technology that would allow students to actually play with an Internet of Things system and a corresponding learning experience that would naturally promote questions around distributed intelligence, elementary robotics, and the Internet of Things.

BACKGROUND

The Internet of Things

The Internet of Things (IoT) is any system where devices communicate wirelessly through the internet. These devices can be anything from everyday objects, such as watches and refrigerators, to complex computing devices. When products are connected to the internet, accessing information and exerting control over them can be done quickly and easily from any location that also has an internet connection and the proper security clearance. This connectivity has applications in areas spanning from personal convenience to remote health monitoring to smart transportation systems (Tiwari & Singh, 2016). An IoT system (see Figure 1) contains three main components: (1) physical devices (things) including sensors and/or actuators, (2) data/device management software, and (3) a data interaction interface. Through

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a connection to the internet, information that otherwise would be difficult and expensive to obtain from physical devices can be easily accessed and leveraged. Most importantly, smart, connected products are changing how people interact with the technology that makes up a large part of the world around them, causing a shift in how technology is both used and designed (Tiwari & Singh, 2016).

IoT in Education

As the Internet of Things becomes more and more integrated into everyday technologies, it is crucial that students begin learning about and interacting with IoT from a young age. Early exposure and interaction with IoT technology will help students understand some of the challenges presented by living in a smart, connected world such as security issues, big data, and data analysis. Project-based techniques are often deployed to teach young students about Science, Technology, Engineering, and Math (STEM) concepts. However, this project-based learning requires both technology tools to facilitate learning as well as curricula to help educators structure and execute these lessons (Capraro et al., 2013). IoT is no exception, and it will require both curricula and appropriate technological tools in order to be incorporated into classrooms both to teach pure IoT concepts and to enrich learning in other STEM disciplines.

While the idea of smart, connected products is becoming more relevant in everyday life, there are very few technologies available to teach young students about how IoT systems work and why they are important. Products such as the Particle Photon, Arduino Uno Wi-Fi, and the Adafruit Feather board are available for makers to purchase and use in their Do-It-Yourself (DIY) projects, but they are not appropriate for or accessible to young students (Adafruit, 2019; Arduino, 2018; Particle, 2019). Platforms that are appropriate for young students, such as Makey Makey and LEGO WeDo lack a connection to the internet, and therefore can't be used to explore the world of IoT ("LEGO Education WeDo 2.0," 2019; Makey Makey, 2019). littleBits, which is a kid-friendly magnetic electronics system, used to have a WiFi extension, but it was discontinued in early 2019. When it was available for purchase, it was cost-prohibitive for most schools at a price of $59.95 for the cloudBit component alone, and littleBits as a platform lacks a build system. The littleBits cloudBit component was also never included in the littleBits educational kits, and it was therefore not being used in classrooms as a way to teach students about IoT (littleBits, 2019). Interfaces such as Scratch and the Tynker App can be used to connect LEGO WeDo and other educational technologies to the internet, but they can only control one device at a time, which significantly limits the diversity of possible creations and gives a limited representation of the power of IoT systems (MIT Medial Lab, 2019; Tynker, 2019).

Despite the lack of technology specifically dedicated to teaching young students about IoT, many classrooms across the United States have still found ways to educate students about IoT and how it can be used. For example, creating a "smart pot" for monitoring plants is a commonly used activity to explore the value of smart, connected products (Davis, 2017). In a curriculum published by the National Science Teachers Association, students are challenged to identify parameters about a plant that is important to measure and design a smart pot to incorporate those sensing features (Davis, 2017). Students would then design their pot using CAD (Computer-Aided Design) software and come up with a paper prototype of how they would want to display the information. The curriculum then states that students could construct their pots using found materials, and cites the littleBits cloud kit as a means to connect the pot to the internet. However, the curriculum also states that students could simply end the activity with a "sketch-based" or "craft-based" model of their smart pot that wasn't connected to the internet and did not contain any sensors (Davis, 2017). These representative solutions fail to enable students to actually engage with engineering artifacts and lack the tangible connection to the engineering design process. Students, therefore, will never encounter any of the challenges or benefits of IoT systems and won't develop a way of thinking about IoT.

While activities like the smart planter are a good starting point for introducing IoT concepts, teachers are left with an inability to enable students to actually create their own smart, connected solutions to engineering design problems. While LEGO Robotics platforms, DIY microprocessors, and other technologies can be used in classrooms to enable students to build functional artifacts, these products are expensive, not easily connected to the internet, and often require additional materials to enable students to truly create their own solutions. Creating a technology that contains an internet-enabled processor, build system, and programming interface specifically designed to enable 1st–6th-grade students to create their own smart, connected products will present a solution to this problem by eliminating the need for projects to end in representative solutions and enabling young students to engage in hands-on learning with IoT systems.

DESIGN GOAL

In this design case, we attempted to lower the barrier to entry to using the Internet of Things with young students by designing and prototyping an IoT platform specifically for the elementary school setting. The goal of this project was two-fold: (1) to create a high-fidelity prototype of a platform and a meaningful learning experience using that platform, and (2) to test and evaluate this technology prototype and learning experience in a real elementary school classroom.

DESIGN CONSTRAINTS

The elementary classroom environment presented several unique design constraints on the task of designing an Internet of Things technology specifically for use by elementary students. We chose this set of design criteria based on our experience in K-6 classrooms.

Design Constraints:

1. Each unit within the system must be connected to the internet
2. Each unit within the system must be powered wirelessly
3. Each main component must be easy to recognize individually among a group of smart hubs
4. There must be a standard build system to construct physical solutions around the main components, sensors, and actuators that is appropriate for students ages seven and up
5. The platform must allow for a diversity of student solutions to any engineering design problem
6. The user interface for coding must be accessible to students ages seven and up
7. The cost of a classroom set must be between \$800–\$2,000 based on the cost of other educational technology platforms (Norris, 2015)

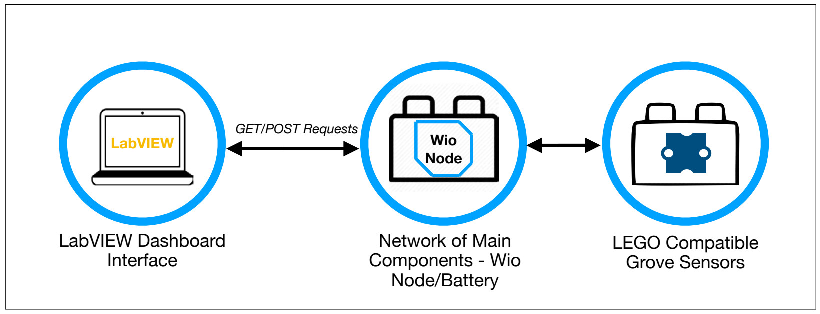


FIGURE 1. Overview of SymbIOTics System.

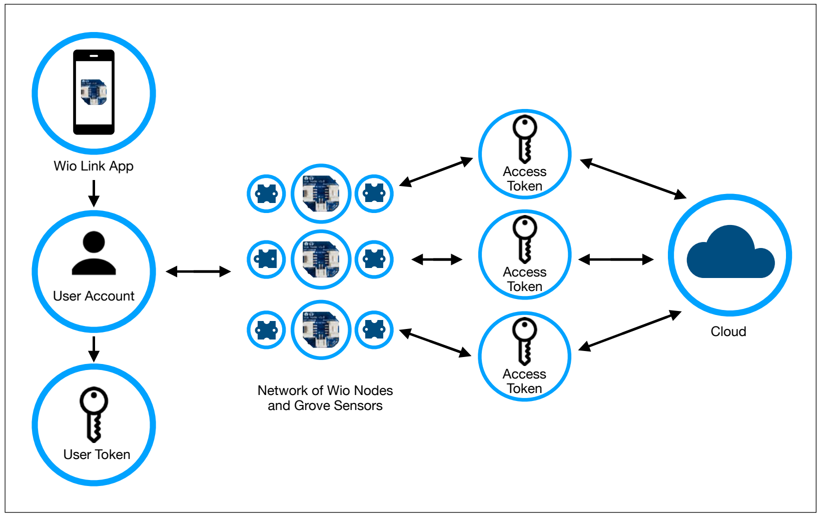


FIGURE 2. Wio Node System Architecture.

TECHNOLOGY CREATION

Keeping the design constraints detailed earlier in mind, we developed the hardware and software for an educational Internet of Things platform. We named this platform SymbIOTics. Altogether, the SymbIOTics system consists of three main components: (1) the smart brick containing the Wio Node and battery, (2) the Grove sensor/actuator modules, and (3) the LabVIEW Dashboard creation interface (see Figure 1).

In the ideal use case, each student in a class would get at least one smart brick and have a variety of sensors and actuators to pick from to bring their ideas to life. Not every student needs to have the same sensor and actuator modules. In fact, selecting the modules becomes part of their problem solving and engineering design process. In total, the cost of one main component is approximately \$15, and the cost of a class set of 30 main components, 30 sensors and 30 actuators would be approximately \$1,000 (Grove System, 2018; Wio Node, 2018).

Hardware Design

Wio Node System

Because the most important aspect of the SymbIOTics platform is its internet connectivity, it was essential to select a microprocessor that would easily connect to a wireless network and stay connected. The Wio Node is a small, low-cost, Wi-Fi enabled board specifically designed for IoT systems that require several different nodes to all communicate with each other. The Wio Node is manufactured and sold by Seeed Studio, an electronics company that also produces and sells Grove sensors and other low-cost electronics products.

At \$9.90 a board and approximately one square inch in dimension, the low cost and compact design of the board make it the clear choice for the intelligence of the SymbIOTics system. To power the main component, we selected a small, lithium-ion battery that can last for up to 5 hours of continuous use while also fitting within a reasonable size for the main component (Data Power Technology Limited, 2015).

Each Wio Node contains two Grove sensor ports, and this ability to use the plug-and-play Grove sensor system was another reason why the Wio Node was selected as the brain of the SymbIOTics system.

The Wio Node system is controlled by the Wio Link mobile app (available for free on both the Apple and Android operating systems). Through the app, users can add Wio Nodes to their account, select which sensors and actuators are plugged into which ports, and wirelessly upload the firmware to the board. This enables the plug-and-play Grove modules connected to the Wio Node to communicate with the Wio Cloud, which can be accessed through a RESTful API using a link and an access token (see Figure 2). A RESTful API is a type of application program interface that uses HTTP requests to read information using the GET command and send information using the POST command

Sensor System

Grove is a modular, plug-and-play prototyping system consisting of base units (usually a microprocessor) and sensor and actuator modules. The goal of the Grove system is to make quality sensors and actuators quicker and easier to use by eliminating the need for soldering and/or breadboarding ("Grove System," 2018). Each Grove module serves a single purpose that can be as simple as a single LED and as complicated as an air-quality sensor. Altogether, the Grove system contains over 50 different sensors and approximately 35 different actuators and displays to allow for a diversity of potential projects. For the SymbIOTics platform, a variety of sensors and actuators that are appropriate for elementary school students were selected, including, but not limited to, buttons, speakers, ultrasonic sensors, LED light strips, and servo motors.

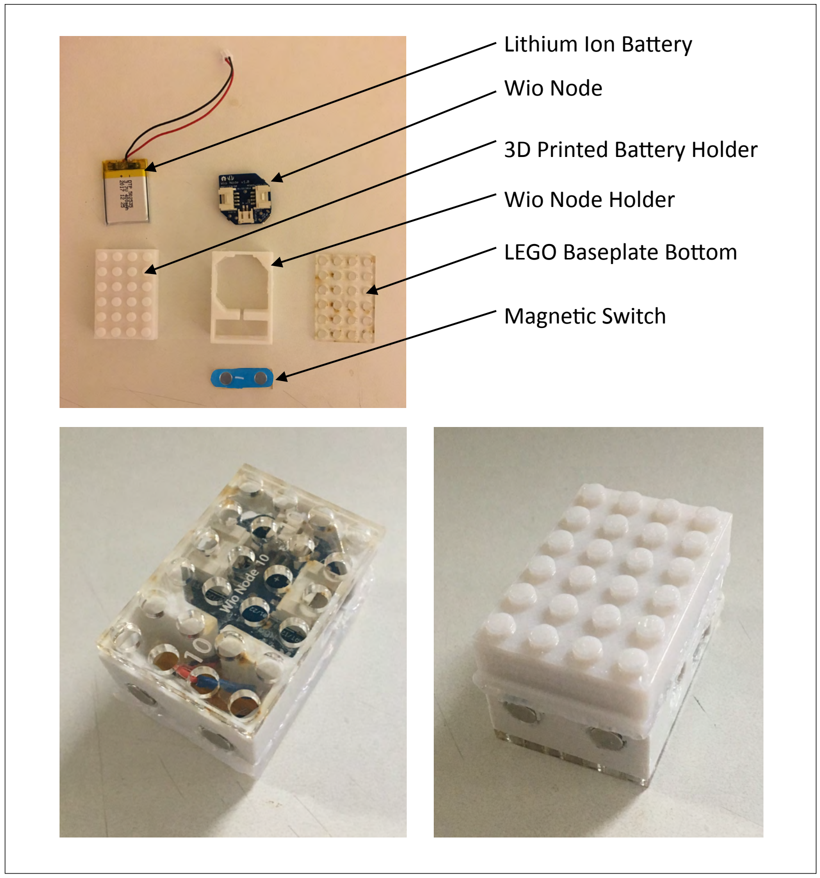


FIGURE 3. (a, top): Main Component Exploded Parts View; (b, bottom right): Main Component Assembled Isometric View; (c, bottom left): Main Component Assembled Bottom View.

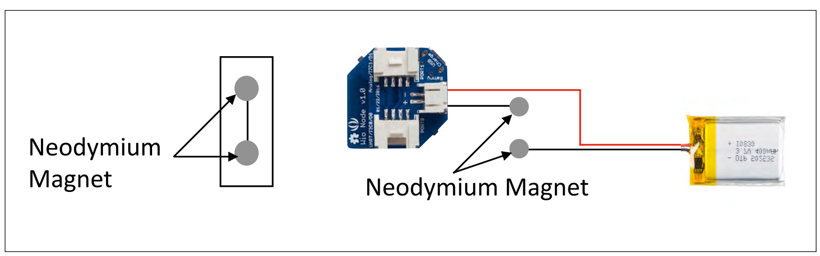


FIGURE 4. (a, left): Magnetic Switch Piece Schematic; (b, right): Wio Node, Battery, and Neodymium Magnet Circuit.

LEGO Build Platform

To allow students to easily construct physical objects that incorporate the Wio Node and the Grove sensors, we created LEGO compatible cases or mounts for all components. This feature enables students to use standard LEGO bricks as the build system for the SymbIOTics system.

The Wio Node and lithium-ion Battery are encased in a 3D-printed LEGO shell (see Figure 3). Together, they make up the "smart brick," which houses all of the intelligence and power for each main component of the SymbIOTics system. To enable users to easily turn on and off the smart brick, the lithium-ion battery and the Wio Node are wired together in a circuit containing two neodymium magnets (see Figure 4a). When users want to turn the smart brick on, they simply take one of the switch pieces (see Figure 4b) that contains two neodymium magnets wired together and connect it to the smart brick. This closes the circuit and turns the brick on. When students are done using the smart brick, the switch piece can be removed, turning the smart brick off. This design allowed for the most compact configuration of the Wio Node and the battery, while also allowing for cordless on/off control. Earlier iterations of the casing design had the battery and Wio Node as two separate pieces that connected magnetically when the Wio was in use. However, this design made it difficult for students to build without turning on and off the Wio accidentally, which is not a problem with the switch design. The top and bottom of the smart brick are LEGO compatible to allow students to create easily around the SymbIOTics system with standard LEGO bricks. The bottom of the smart brick is a laser-cut baseplate, which is not only functional for attaching LEGO bricks but also serves as an area for the name of the smart brick and the location of the ports to be etched for easy identification.

The Grove sensors were mounted on 1/8" acrylic laser-cut mounts with LEGO-compatible holes around the outside (see Figure 5). This enables students to build with LEGO bricks and attach any Grove sensor to their creation.

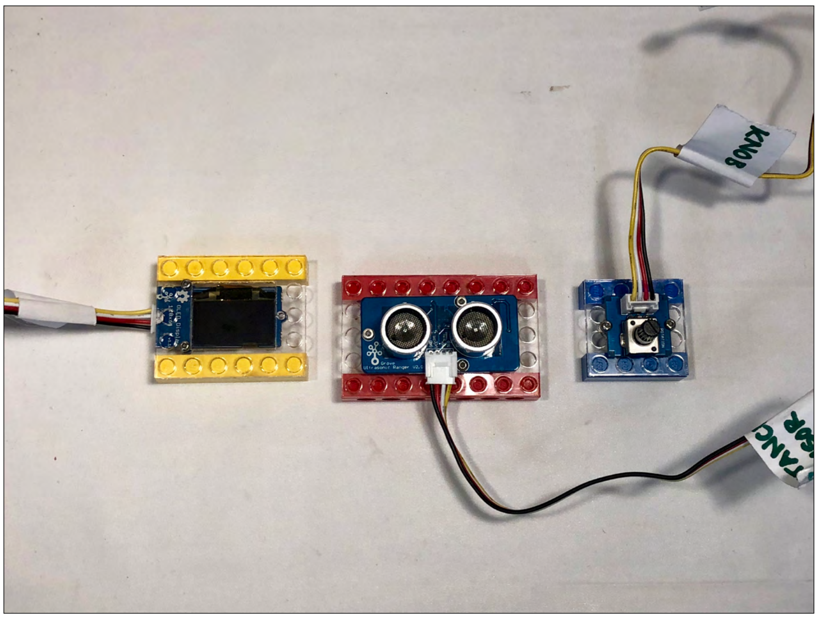


FIGURE 5. Example Grove Sensors/Actuators with LEGO Mounts.

Software Design

Overall Code Architecture

We developed an interface that allowed students to quickly and easily interact with the Wio Node system without having to write their own code. The software was written in LabVIEW software, a graphical programming language commonly used by engineering students and professionals (National Instrument, 2019).

To configure the software, all the Wio Nodes for one class must be added in the Wio mobile application using one Seeed Studio account. By logging into this account, the account owner can find their user token. Entering this single token into the LabVIEW Dashboard interface generates a list of available nodes from that account. This list is then populated to each of the dashboard objects corresponding to each Grove module. These dashboard objects contain a user control for the name of the Wio into which the module is plugged, the port to which it is connected, and other relevant parameters. Dragging and dropping these different items onto the dashboard automatically populates the back panel with the necessary code. For the user testing conducted in this study, all of the nodes were added to one account prior to being used in the classroom, and the user token was populated through the software. Figure 6 shows a graphical representation of this code architecture.

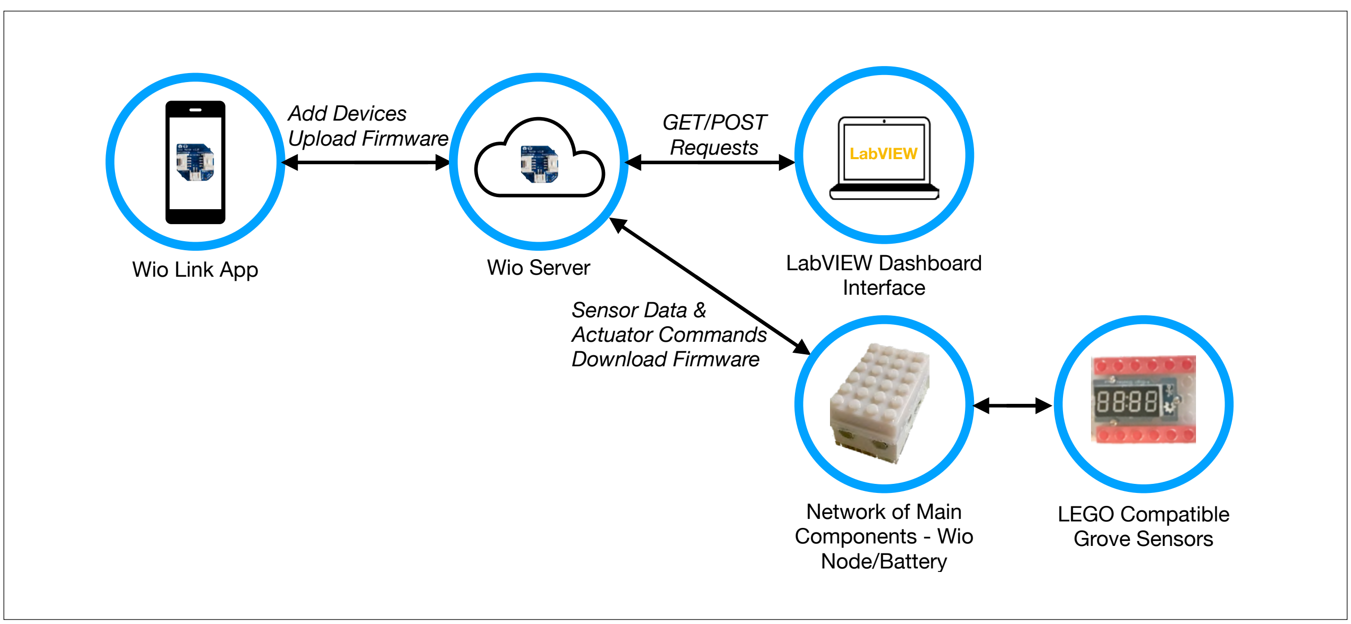


FIGURE 6. Overall Code Architecture.

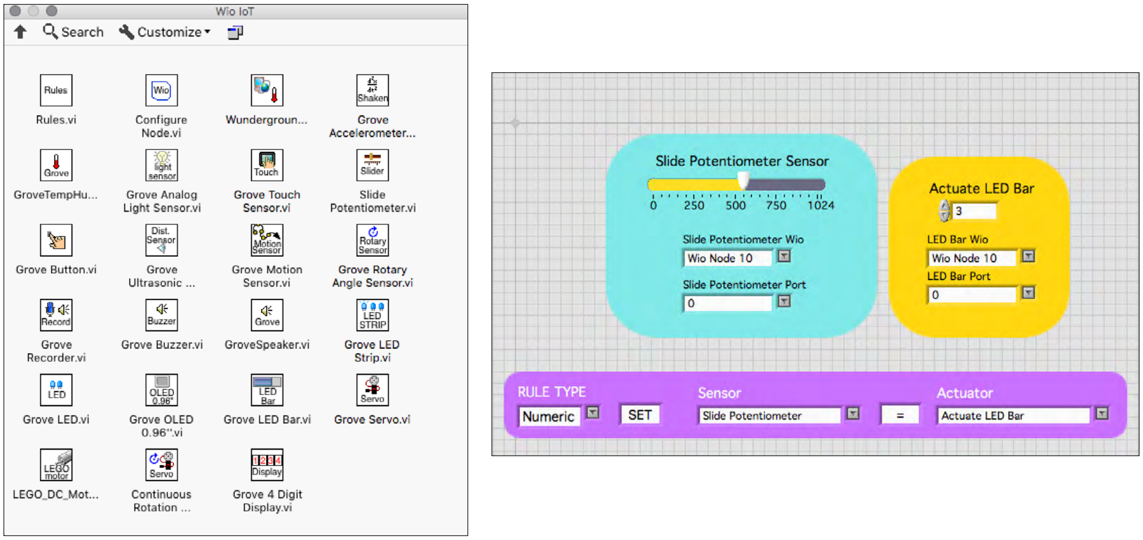


FIGURE 7. (a, left): SymbIOTics LabVIEW Palette; (b, right): Example SymbIOTics Dashboard.

Users can write simple rules that control the behavior of an actuator based on a sensor value. There are two categories of rules: Boolean rules and numeric rules. Boolean rules relate a truth value for a sensor to a truth value of an actuator. For example, "If a button is pressed, then turn on the LED" is a Boolean rule. The rules section of the SymbIOTics LabVIEW code automatically populates the rule dropdowns with the sensors and actuators present on the dashboard, and sets the actuator Boolean equal to the sensor Boolean. A numeric rule maps the value of a sensor to the value of an actuator. For example, the value of a light sensor can be mapped to the number of lights to be lit up on the LED light strip so that as the sensor value gets lower (darker), more LED lights will be lit up. This all happens automatically without the user needing to write any code themselves.

User Interface

Since the SymbIOTics system is designed for students ages 7 and up, the goal was to make the coding interface as simple as possible. Students simply select the module they want to add to the dashboard from the SymbIOTics palette and drop it onto their dashboard. From there, they can move the object around and change different controls as desired. All user-controlled components of the interface are either drop-down menus, clickable buttons, or numeric controls, eliminating the need for students to write text-based code. Students can also drag images onto their dashboard and double-click to type text.

Figure 7 shows the SymbIOTics palette and an example dashboard. We labeled each module item with the name of the Grove module and the different controls or indicators that correspond to that module. Students can control the sensor/actuator from the corresponding dashboard module. Students can also drag a "Rules" module onto their dashboard, which allows them to create a correlation between a sensor and an actuator.

The rules are set up like an "If this, then that" statement. Students can select a sensor and have the value of that sensor to control a selected actuator. For example, if a student wanted the buzzer to buzz every time she pressed a button, she would set up the rule to say, "If button sensor pressed, then buzzer actuate." For sensors/actuators that are non-binary, users can write a "set X equal to Y" statement that will automatically map the value of a sensor to the value of an actuator. For example, a user can write a rule so that a temperature sensor can control the number of LEDs lit up on a light strip by selecting "set the number of LEDs lit up on the light strip equal to the slide potentiometer sensor value." This will take the slide potentiometer reading and scale it appropriately such that as you move the slider from one end to the other, the number of LEDs lit up on the LED light strip increases/decreases appropriately. If there are multiple instances of the same type of module, i.e., two different buttons or two LEDs, the interface will automatically number them to distinguish between the instances.

Each different component is color-coded. The sensor components are blue, actuator components are yellow, and the rules are purple. If a sensor component is placed on the dashboard but can't be read due to a connectivity problem, the sensor indicator will be grayed out, indicating to the user that there is a problem with the reading.

Known Software Limitations

While the SymbIOTics software system is fully functional, it has several limitations in its present state. Currently, the SymbIOTics system is functional only with a Seeed Studio account and the Wio Link mobile app. The mobile app is needed to add main components, name main components, and upload firmware for the desired sensors and actuators. In addition, each new user account will have a new user account token. In order to use the SymbIOTics dashboard software, this user account token needs to be inserted into each layer of the code. The SymbIOTics system also currently has a hard-coded refresh rate of one second for checking sensors and updating rules. In future iterations, this refresh rate would be accessible for the user to control as desired.

Another important limitation of the SymbIOTics system is its dependence on an accessible Wi-Fi network. Each Wio and each laptop being used must be connected to a Wi-Fi network in order for the SymbIOTics system to function. In this study, a mobile Wi-Fi hotspot was used to avoid reliance on the secured school network. However, the need for devices to be connected to a Wi-Fi network, while an inherent part of IoT, does pose logistical challenges in most formal learning environments.

PILOT STUDY AND INITIAL FINDINGS

Description of Pilot Study

We conducted a classroom pilot study to evaluate the effectiveness of the new Internet of Things platform. The goal of this user test was to observe how the new technology functioned in an elementary school classroom and determine if it could in fact be used as a tool for young students to learn about IoT systems. The study site was a second-grade coding class at a private day school in New England that is dedicated to encouraging students to think critically and uniquely about the world around them. The study site serves grades pre-kindergarten to eight and has a 6 to 1 student-teacher ratio with an average class size of 14. 20% of students receive financial aid, and 36% of the student body are students of color.

Students participate in rotating special area classes throughout the year. Each special area class meets for one hour three or four times a week for approximately six weeks until students switch to the next special. This coding class is one of the special area classes in which all second-grade students partake over the course of the school year. The overall goal of the coding class was to introduce students to computer science by using different coding platforms to solve engineering design problems. Students may have been exposed to LEGO WeDo robotics and/or some coding with Scratch Jr., but they had received little to no prior formal instruction on robotics, coding, or IoT.

We tested the SymbIOTics platform in both sections of this coding class with eight and seven students in each section, respectively. Each section had three one-hour sessions with the technology. The duration of each session was determined by the length of a typical class period at the study site. Three class sessions for each section were selected for the pilot study based on the schedule of the coding teacher. The coding teacher had content selected for the other class sessions and wanted to make sure that her students were exposed to other concepts and technologies before they moved on to the next special area class. Aside from the scheduling constraints, three one-hour sessions seemed sufficient to achieve the pilot study objectives of: (1) determining if the technology was functional in a classroom setting, and (2) identifying what value was added by using

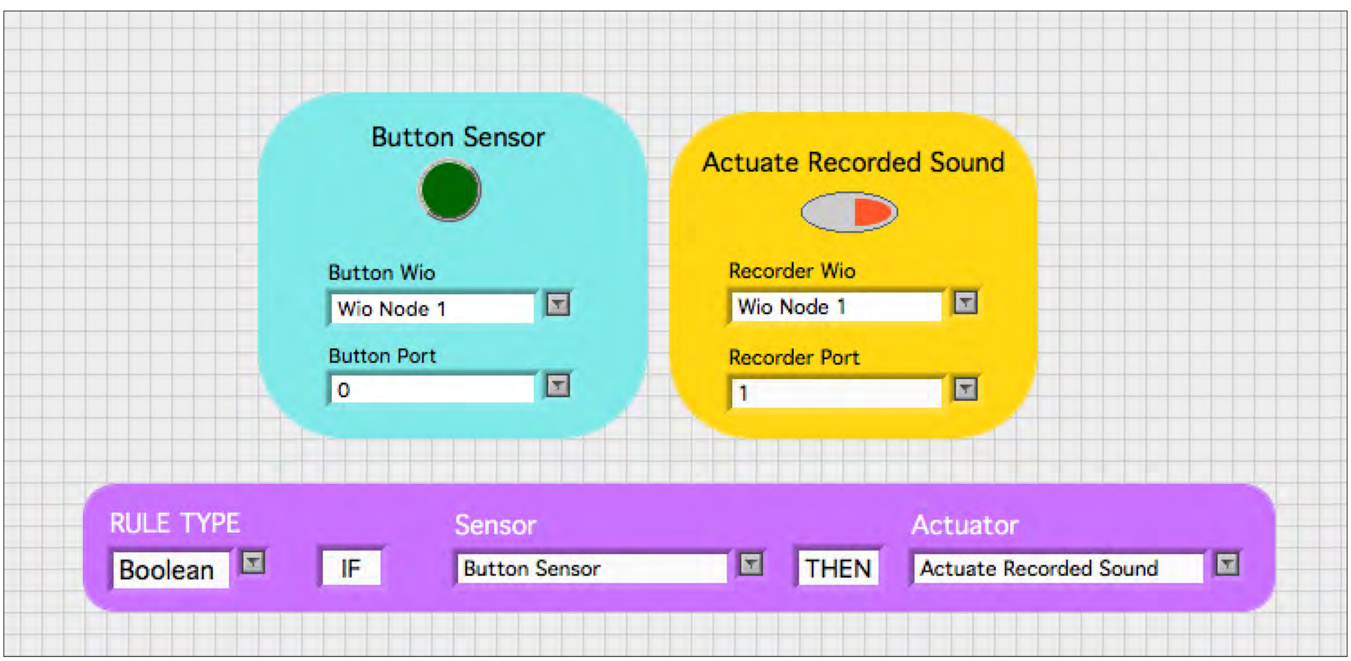


FIGURE 8. Dashboard Given to Students During First Class Session.

the IoT technology in the classroom. The sessions were led by the first author with support from the coding teacher.

In the first session, students completed activity 1. We briefly introduced them to the idea of IoT by brainstorming different things from everyday life that are already connected to the internet. Next, we introduced the SymbIOTics platform and gave students a smart brick, a button sensor, a recorder/speaker module, and a pre-made dashboard (see Figure 8). When we introduced the SymbIOTics system and told students that they would get to build their own IoT creations using the hub, actuators, and sensors, we discovered that many students didn't know what sensors and actuators were. We explained that sensors measure different types of information, and actuators perform various types of actions. Every student then successfully turned on their smart brick using the magnetic switch.

Next, the first author challenged students to use LEGO bricks to create an animal. The animal theme was chosen because it is a subject with which all second-grade students are familiar, and it ensured that the activity itself would not be challenging for students. This way, the functionality of the technology could be evaluated without concern that the activity itself was preventing students from being successful. We asked students to use the recorder module to record the sound their animal makes and then actuate the playing of that sound using the Grove button. Lastly, we asked students to change the button being read to one of their friend's buttons, so that their animal's noise was actuated by a button that wasn't their own.

During the second and third class session, students completed activity 2. In the first class session for activity 2, we challenged them to incorporate one Grove sensor and one Grove actuator into a zoo exhibit featuring the LEGO animal they built in the first class session. The next step was to build a dashboard for a zookeeper that had information about not only their animal but also some of the other animals in the class.

During the third class session, students continued building their zoo exhibits and constructing their dashboards. At the end of the third class session, students shared their exhibits and dashboards with the rest of the class and had a debriefing discussion about what they learned, what they liked about the new technology, and what they wished was different.

The main two learning objectives for students across the two activities were to be able to describe how (1) data from lots of different types of sources can be combined to tell a story and convey important information and (2) IoT systems are a means for both sensing (data collection) and actuation (making things happen) based on data.

Pilot Study Overall Findings

Overall, the SymbIOTics system performed as expected when used in a second-grade classroom. Students successfully combined LEGO building bricks with the SymbIOTics hub, actuators, and sensors to complete hands-on activities exploring the Internet of Things. Students created a diverse set of solutions to an engineering design prompt and easily used the technology to integrate IoT concepts into their thought processes and design solutions.

Students also successfully used the LabVIEW dashboard interface to read the sensors, control actuators, and write rules. While students clearly understood the purpose of the computer interface, they were very unfamiliar with using laptops and struggled to use the trackpad for actions such as dragging items onto the dashboard and clicking on drop-down menus. In addition, the use of the Wi-Fi hotspot was effective, but it slowed the system response time down to about 5 seconds. While this significant delay caused some initial confusion, it sparked an interesting and valuable dialog about how the technology was working, and it did not prevent the main learning objectives from being achieved. Additionally, students were excited to see their creations come to life and happily shared their success with classmates and the instructors. In the following paragraphs, we present the findings from conducting each activity with the second-grade students.

The opening question of the first class session provided useful information about students' initial ideas about the Internet of Things. In response to the prompt, "What is the internet?" many students gave examples of tasks that people use the internet to do (e.g., web searches, video streaming, gaming), but none of them described the internet as a network with many things connected to it. After brainstorming examples of things that are connected to the internet, such as cell phones and gaming systems, students excitedly discussed the functionality that could be added to everyday items by connecting them to the internet. One student was particularly excited about the idea of connecting her sneakers to the internet so she could track her steps. Other students came up with common IoT applications for kitchen appliances and other household objects such as the lights and the television.

Findings from Activity 1

For the first activity, every student successfully built an animal, recorded the sound that animal made, and actuated the playing of that sound using the button. Students were given the hub with the recorder/speaker module and the button module already attached, as well as the dashboard with the rule already written. Figure 9 shows examples of the LEGO animals that students created.

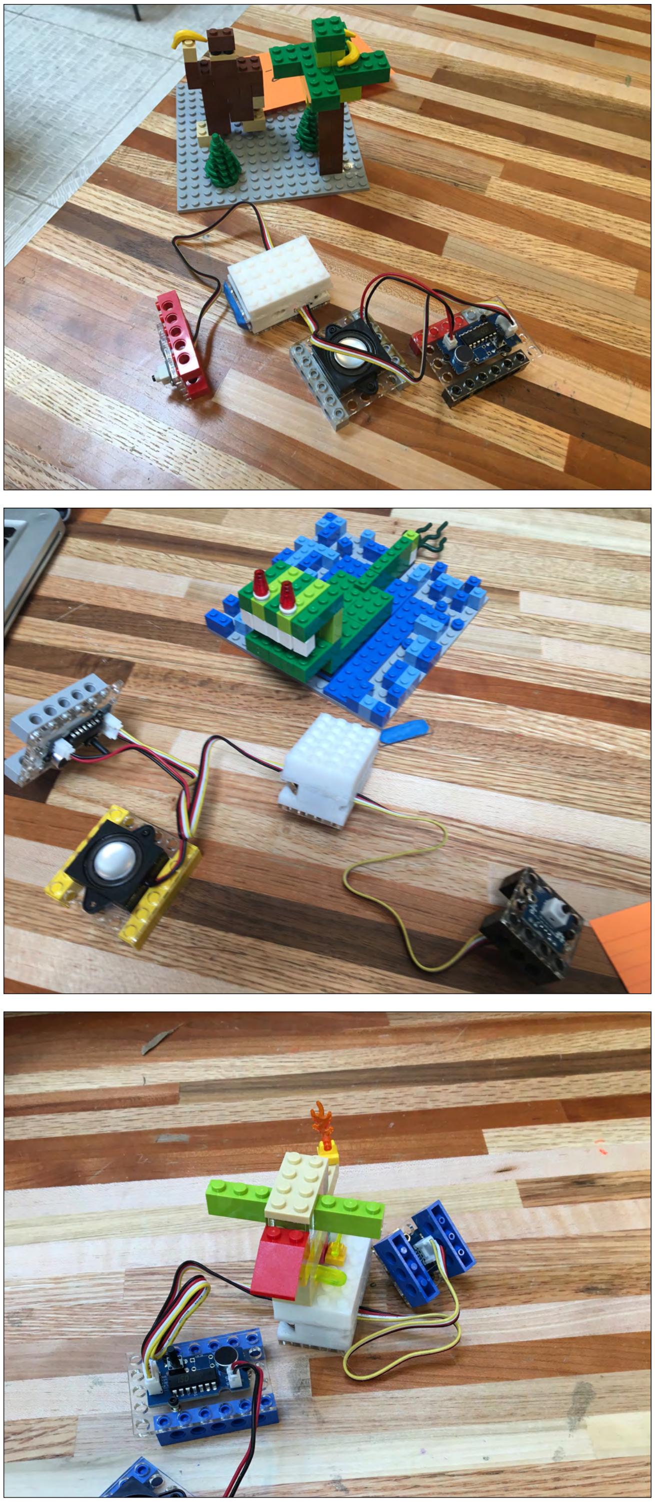


FIGURE 9. (a, top): Student build of a monkey; (b, middle): Student build of an alligator; (c, bottom): Student build of a bird.

We observed that while students were excited to build a LEGO animal and enjoyed getting to record and playback sounds, they were hesitant to incorporate the brick into the animal they were building. All of the students in the first section and all but two of the students in the second section kept the SymbIOTics components completely separate from the LEGO bricks they were using to build their animals. This was in large part due to an unfamiliarity with the components and a fear of breaking them. Even though the example animal showed the LEGO duck placed on top of the SymbIOTics hub and connected to the speaker and the button, students still left the hub and other components out of their creations. However, after the classroom teacher and the first author re-emphasized that they could build with the hub and all other components, the majority of the students began to actually incorporate the SymbIOTics components more directly into the models they constructed.

In the second part of activity 1, when challenged to make their button control the playing of someone else's animal noise, students immediately said that they should change the name of the hub being controlled on the dashboard. They all appeared to understand that the name of the hub determined where the desired commands were being sent. One pair of students, however, changed the hub they were controlling on both the button sensor and the recorder components of the dashboard. When they pressed their button, they were confused about why nothing happened. Since they had changed the name of the hub on both the button component and the recorder/speaker component, their button was no longer controlling anything. After discussing this with the first author, the two students identified the change they needed to make and successfully actuated their friend's animal using their button.

The main goals of activity 1 were to: (1) test the SymbIOTics platform's technical viability in a classroom environment, and (2) introduce students to both the Internet of Things and the SymbIOTics system. The first goal was achieved throughout the activity as the main bricks stayed powered on, connected to the internet, and functioned as expected for the duration of the class. The dashboard interface and physical components were all used by the students and did not break or experience any serious malfunctions. The second goal was achieved through both the initial discussion of IoT and the building activity, where students were given the opportunity to explore IoT by building an internet-enabled creation.

Findings from Activity 2

In the second activity, we gave the students a smart brick with one random sensor and one random actuator, each labeled with a tag stating what they measured/actuated. For example, an ultrasonic sensor (which measures the distance to an object) is not something with which most second grade students are familiar, and it is not obvious what the

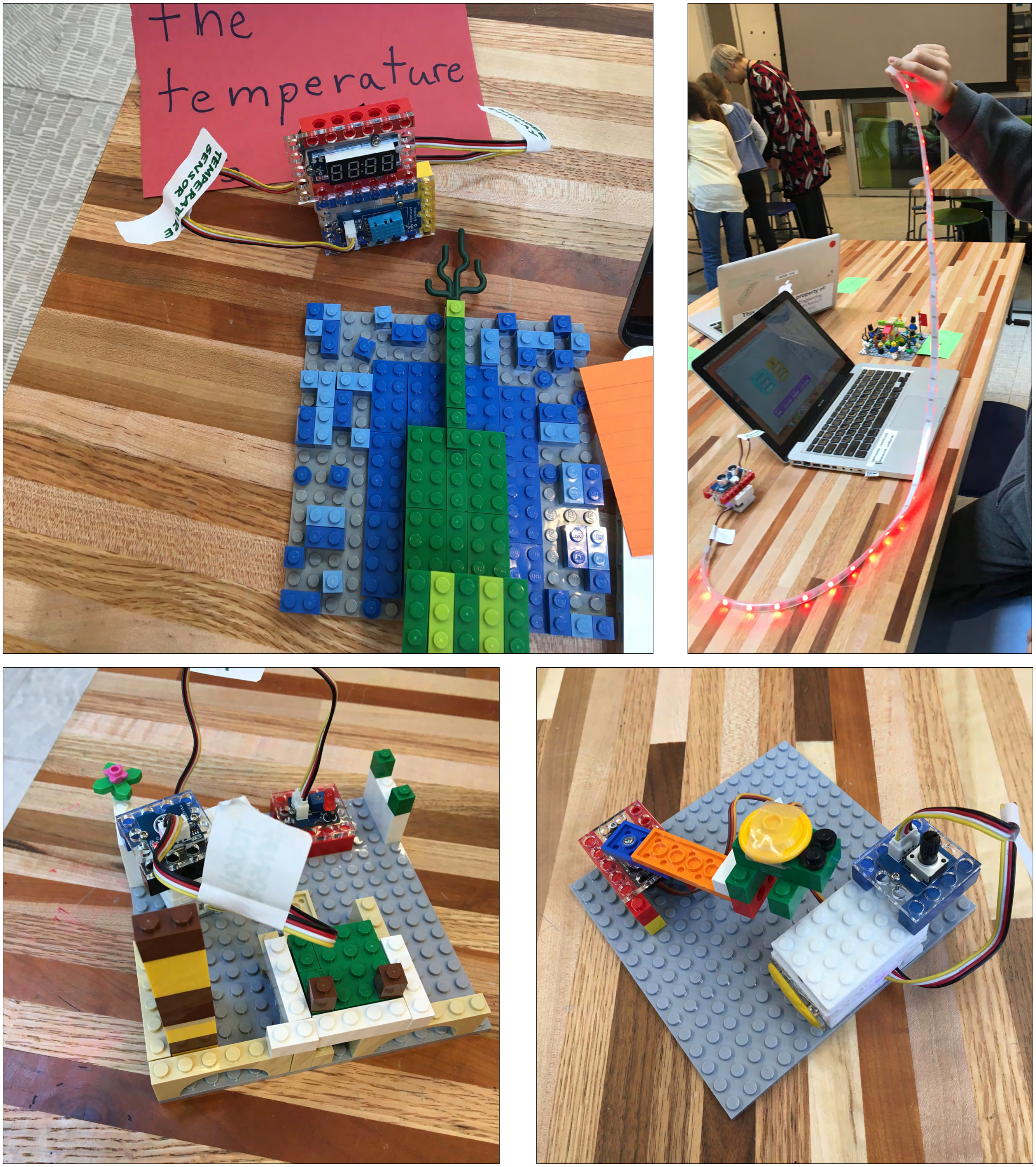


FIGURE 10. (a, top left): Alligator with temperature sensor and numeric display; (b, top right): Petting zoo with emotional meter; (c, bottom left): Giraffe with touch sensor and LED; (d, bottom right): Turtle mounted on servo motor controlled by potentiometer.

sensor measures from simply looking at it. To help students understand what the ultrasonic sensor measures, its tag says "distance."

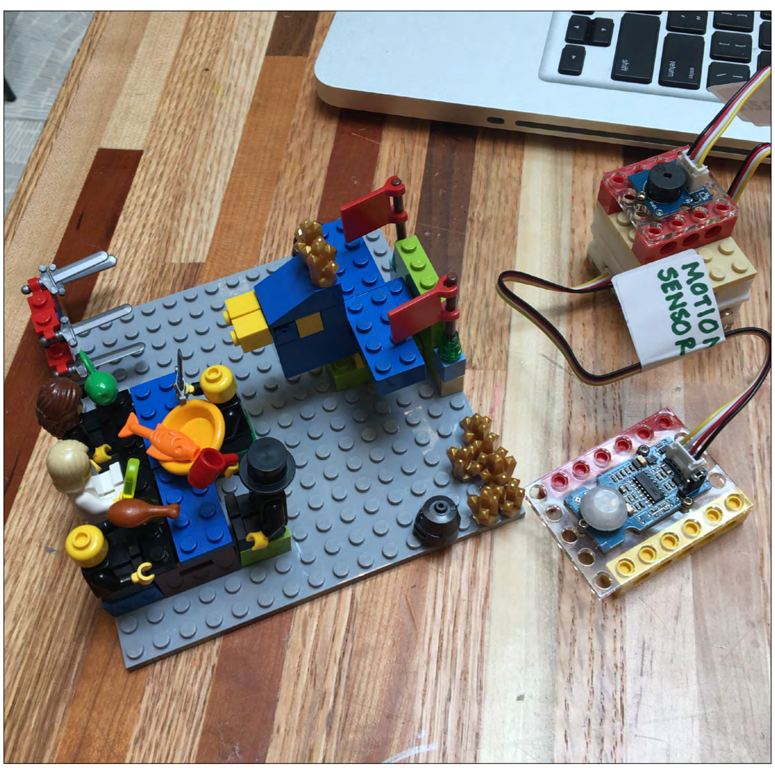
Every student successfully incorporated a sensor and actuator into their animal's zoo exhibit. This means that each exhibit had a sensor measuring some value and an actuator module performing some type of noticeable output. Some examples are shown in Figure 10. Students developed and constructed these ideas independently. Figure 10a shows an alligator exhibit that has a temperature sensor measuring how cold the water is and displaying it on the numeric display. Figure 10b shows how a student used the LED light strip as an emotional meter for his petting zoo exhibit. The color of the lights and the number of lights lit up on the strip indicate to the zookeeper how the animals in the petting zoo are feeling. This student also used the ultrasonic sensor to measure how close visitors were getting to the animals in the petting zoo. Lastly, Figure 10c shows a giraffe exhibit with a touch sensor and an LED Light. If the giraffe gets hurt, it can touch the touch sensor, which will turn on the light to tell the zookeeper that something is wrong. Figure 10d shows a handicapped turtle mounted on a servo motor. Visitors at the zoo can use the knob to move the turtle to different positions since it can't move around on its own.

In order to bring these animal exhibits to life, students had to drag the sensor and actuator modules onto their dashboard and select the name of their smart brick as well as the port the sensor/actuator was plugged into. Most students were able to do this independently, and those that did need help were often struggling with using the trackpad, not struggling to properly use the interface. Once students had set up their dashboard to read the sensor values and make something happen with their actuator, we encouraged them to add rules to the dashboard. Every student successfully created a rule, but not all of the students decided that they wanted to use the rule in their final design. Some preferred to control their actuator using the manual control on the dashboard. When asked why they preferred using the manual control, students' responses reflected that the manual control fit better into the narrative they were telling about their zoo exhibit.

After students had their own zoo exhibit completed, they were challenged to improve their dashboard so that a zookeeper could use one interface to see information about and control components of many of the different exhibits. To do this, students figured out that they needed to drag additional sensor and actuator modules on to their dashboard and select the appropriate hub name and port number.

Analysis of Student Artifacts

We saved and analyzed all fifteen student dashboards for the number of different components used by the students. All but three students were able to incorporate at least one SymbIOTics hub that wasn't their own. Most dashboards contained only one of two sensors but between two and six actuators, indicating that most students were more



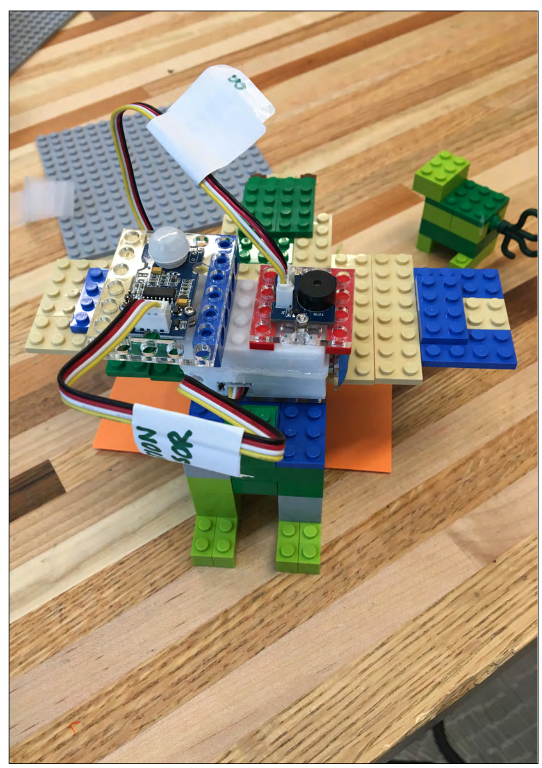


FIGURE 11. (a, left): Bird with motion sensor/buzzer; (b, right): Cat with motion sensor/buzzer.

interested in controlling each other's actuators than they were in reading in sensor information. In addition, five out of the fifteen students wrote at least one rule that created a relationship between a sensor and actuator from different smart hubs.

We also analyzed students' dashboards for the diversity of solutions to the design challenge in activity 2. We view solution diversity as an indicator of whether or not the physical devices provided students with a modular and easy to use tool. If every student used the SymbIOTics system in exactly the same way, producing exactly the same solutions, that could indicate that the overall system failed to support imagination and innovation. If students incorporated the SymbIOTics components in a diversity of ways, that could indicate that the platform is successful in inspiring student thinking and being an effective tool for project-based learning. Since every student in each class was given a hub with different sensors and actuators, it was hard to measure solution diversity within a class section, since the materials given inherently produced different student creations. However, between the two sections, there were two students that had the same sensor/actuator combination. Comparing the work of the students who were given the same materials revealed that no sensor/actuator combinations were incorporated into the animal exhibit in the same way across the two sections. Figure 11 shows one example of the comparison of the same sensor/actuator combination being used in different ways. Figure 11a shows the use of the PIR Motion sensor to protect a bird's food. When the sensor detects motion near the food, the buzzer goes off, signaling that some other animal might be trying to steal it. Figure 11b shows how the same sensor was used to determine if the cat was being pet. If the motion of the petting was detected, then the buzzer would go off, representing the cat purring. This is just one example of how different students incorporated the sensors and actuators into their designs in unique ways.

The main two learning objectives for activity 2 were for students to be able to: (1) read from and write to sensors and actuators that are connected to their own smart brick as well as classmates' smart bricks, and (2) use the SymbIOTics system to tell a story and communicate their ideas. Both of these learning objectives were achieved. Students collected different information from the animal exhibits to convey important information to a zookeeper. To accomplish this, students used the Internet of Things as a means for both data collection and making things happen based on that data. Most importantly, students completed these objectives through a variety of solution paths and ideas, which indicates that the technology itself was intuitive enough for students to integrate into their engineering design processes.

ANALYSIS OF DESIGN BASED ON PILOT STUDY RESULTS

Overall Analysis of SymbIOTics System

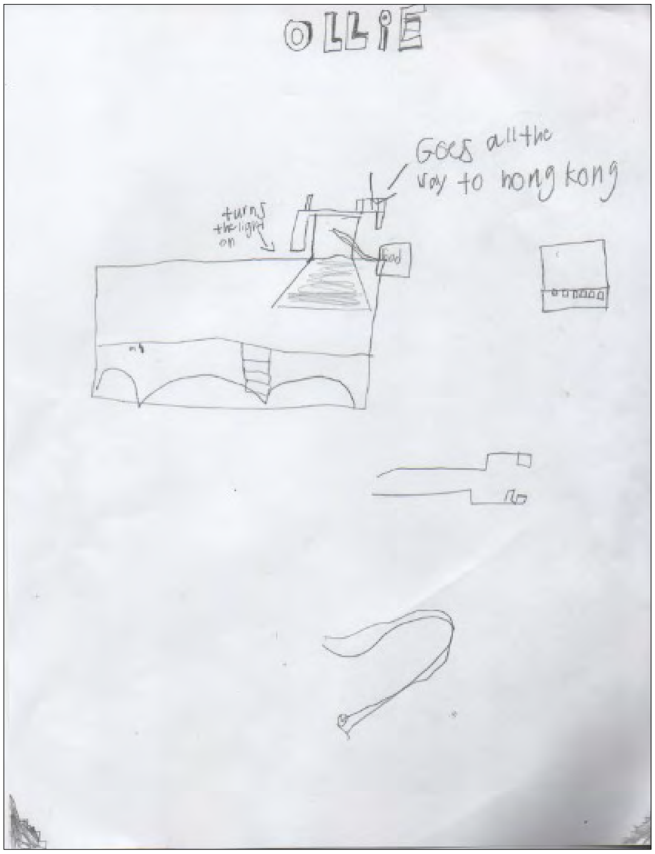
We developed the SymbIOTics system to enable elementary school students to learn about the Internet of Things by building their own smart, connected products. Despite some minor limitations due to network speeds and software interface, the SymbIOTics system is a fully functional prototype of a technology platform designed specifically for elementary school classrooms. While the five-second latency between user input to actuator/dashboard interface output was longer than desired, it did not hinder students' ability to interact with the system and understand how the technology worked. With a technology system successfully developed, we were able to conduct user testing in a formal learning environment.

Despite efforts to design a system with classrooms in mind, the SymbIOTics system does still present schools with significant barriers to entry for using IoT technology with students. The major barrier to entry is the internet connection itself. While mobile hotspots, such as the one used in the testing documented in this paper, eliminate the need to access the school's Wi-Fi network, they require a strong cellular network signal, limit the number of devices that can be connected at a time, and are a financial burden. Finding ways to simplify the process of connecting systems of devices to an internet network will be an important improvement for future iterations of this system and other similar systems. In addition, creating a software interface for managing devices and interacting with them that can be run on a variety of different computing devices will be very important. Most schools do not have an abundance of laptops and need a software that can be run on tablets and Chromebooks to accommodate whatever devices are available. Keeping the unique needs of elementary school classrooms in mind through future rounds of development will hopefully eliminate many of the barriers to entry for using this technology and enable more students to have access to learning experiences centered around IoT systems.

Analysis/Design Changes Needed for Hardware

Overall, the physical design of the SymbIOTics system was successful during classroom use. Students were able to use the magnetic switch piece to independently turn on and off the brick. The LEGO studs on the smart brick and the mounts on the Grove sensors/actuators were also successful in enabling students to seamlessly use LEGO pieces to build their IoT creations.

While the physical aspects of the system are all fully functional, there are improvements that could be made in future iterations based on observations made during the pilot study. Adding a magnetic holder to keep the switch piece



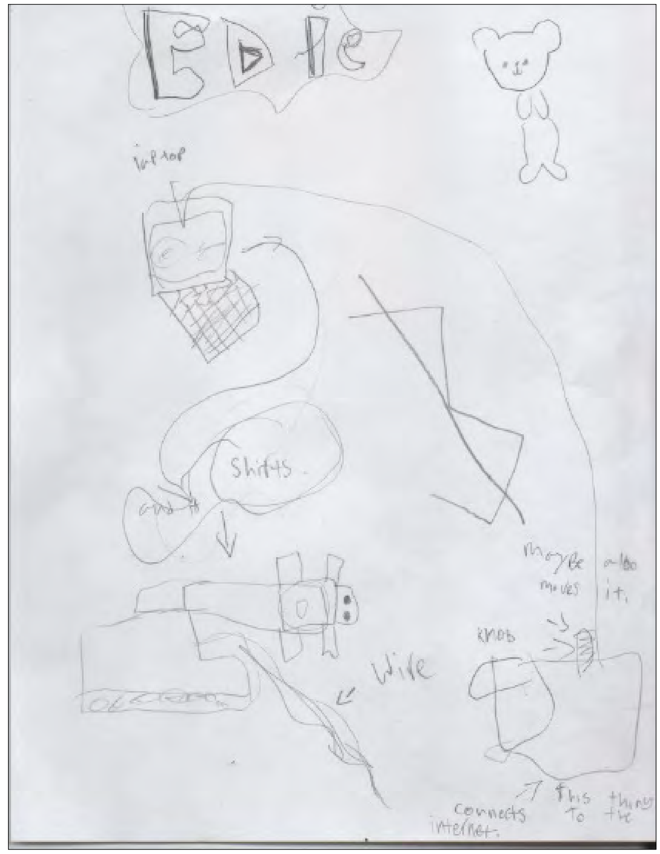


FIGURE 12. (a, left): Student schematic of alligator zoo exhibit; (b, right): Student schematic of turtle zoo exhibit.

attached to the smart brick when the user wants the device to be off would eliminate the need to store the switch pieces separately.

The size of the smart brick could also be made slightly smaller. The size discrepancy between a regular LEGO brick and the smart brick was slightly too large. As illustrated by Figure 10 and Figure 11a, very few students incorporated the smart brick directly into their design. Rather, it was left off to the side or used as a building platform instead of a component that could be a part of their animal and/or zoo exhibit. Figure 12b shows one of the few examples of when the smart brick was actually used as a true building component. Finding a smaller battery to allow for a more compact smart brick would help make it easier for students to incorporate the smart brick directly into what they are building, instead of feeling the need to keep it separate.

Finally, differentiating sensors and actuators using color-coded mounts would have helped make it easier for students to understand what was being measured or controlled. Matching the color of the mount to the color of the computer interface module would be a helpful improvement for future iterations of this system.

Analysis/Design Changes Needed for Software

The SymbIOTics software interface, while fully functional, could be improved in several ways to enhance the overall functionality of the SymbIOTics system. The largest shortcoming of the LabVIEW Dashboard Interface is the lack of a device management system. Users are forced to use the Wio Link smartphone app to add smart bricks, change Wi-Fi Networks, and upload new firmware. This means that students were not able to independently select sensors and actuators and instead were assigned a brick with the appropriate firmware pre-uploaded. This was done to prevent using the already limited amount of instructional time by having to upload the firmware. However, giving students the freedom to select their own sensors and actuators and upload their own firmware would greatly enhance the overall system. In order to add this device management component to the SymbIOTics system using the Wio Nodes, an independent server would need to be created separately from the servers Seeed Studio owns and maintains. Alternatively, each Wio Node could be paired with just one sensor permanently, creating a unit that would act as a "smart sensor" and eliminate the need to upload the firmware. However, this would increase the overall platform cost and increase the size of the sensors.

Another important revision that could be made to the SymbIOTics system is the overall layout and aesthetics. On several occasions, students were unclear if sensor data were being read because the numeric indicators for sensor values were too small and surrounded by other information. While the LabVIEW interface was functional, students were unfamiliar with the palette layout and generally had a hard time interacting with the dashboard because they had to use a laptop with a trackpad. Most young students are more familiar with the touch screen, so revising the interface to be functional on a tablet would also make the dashboard easier for students to interact with.

Lastly, the rules component of the dashboard interface should be expanded upon to allow students to create more complex relationships between components. Currently, the rules are set up to relate two Boolean values together or two numeric values together. A Boolean sensor can't control a numeric actuator, and vice versa. Changing this so that any sensor and actuator could be paired together would allow for greater solution diversity and prevent confusion caused when students tried to create rules between modules that couldn't be paired together. In addition, adding a feature to allow for numerical and comparison statements instead of simply setting sensor values equal to actuator values would also allow for students to create more complex systems. For example, in future iterations, students should be able to write a rule that says "if the sensor value is greater than five turns on the actuator" or "set the actuator value equal to the sensor value plus ten".

OUR FUTURE DESIGN PRINCIPLES

Based on the findings from this initial technology prototype and the pilot study, there are three key design principles that we plan to apply to future iterations of this technology or other technological tools/learning experiences we design with the goal of teaching young students about the Internet of Things.

Design for the Creation of Global Systems

Most often, in classrooms, students are creating their own local systems that serve a single purpose. However, their local systems are limited by the resources they have in their immediate possession and usually lack the ability to communicate with other devices. By leveraging the Internet of Things, students are able to build more powerful systems that are no longer limited to only the resources they physically possess. The technological capability presents a rich opportunity for students to experience how they can be more powerful when they connect to the outside world and collaborate with others than they can be on their own. Technologies and learning experiences used to teach IoT must be designed to easily enable students to create their own systems that can interact with the systems their classmates create, and even external devices and data sources.

As seen in the pilot study, students were excited to create a dashboard for the zookeeper so that they could monitor all of the zoo exhibits, not just their own. Providing a software interface where they could easily see information from any device in the class facilitated the creation of these class-wide dashboards. Additionally, by limiting the number of sensors that could be plugged into one hub, students were naturally encouraged by the technical limitations to collaborate with others. One sensor and one actuator have limited potential and therefore forces students to leverage their classmates' systems. The true learning around IoT comes not from the technology or curriculum itself, but from getting students to think outside of the system, they have on the desk in front of them.

Embrace the Process of Connectivity

We believe that a large part of learning about the Internet of Things is understanding how the connection and communication between systems is working. In an effort to simplify this process for young students, some designers may feel it would be best to hide the connection process from students altogether. However, in the pilot study, we found that the process of having students select which smart brick they wanted to control within the software was where many of the most fruitful discussions began.

The way that the interface allowed users to have control over which device they talked to and the ability to quickly and easily change or add devices was critical for getting students to build their global system (dashboard for a zookeeper). Iterating on this idea and creating interfaces with easy visualization and the ability to switch between devices and interact with many devices at once from one interface is a key part of an IoT technology. Exposing control of connectivity options in a way that is accessible to young students will be an important component of any educational IoT system.

Understand the Constraints of School

While the use of internet-connected technology in schools presents many opportunities, it also presents many challenges. Lack of available teacher trainings, low technology-to-student ratios, and lack of access to appropriate infrastructure (internet, electrical power, etc.) are just some of the many obstacles that prevent most forms of digital technology from being beneficial in the classroom (Johnson et al., 2016). The dependence of the Internet of Things on a robust and stable network amplifies these challenges in a unique way.

In the pilot study described earlier, the technology developed was a completely self-contained system. Through the use of mobile hotspots and laptops we had available, the entire system was brought into the classroom in working order. The teacher/students did not have to reserve school computers, do any software installation, connect devices to the school internet network, etc. The pilot study occurred during a coding class where students are used to the idea of trying out new technologies, a practice that students in other schools may not be familiar with. Additionally, the first author was present to act as a technology expert and troubleshooter when the technology did not behave as expected. While the pilot study reflects how powerful an IoT platform for elementary school students could be, it does not explore what the initial experience would look like for classrooms receiving IoT technology out of the box. If technology is not designed with the realities and challenges of classrooms in mind, then it will likely never reach the hands of students and will, therefore, not be an effective learning tool.

RESEARCH EFFORTS

While the purpose of this paper was to document the design of the SymbIOTics system and the learning experience paired with it, our future goal is to conduct a learning sciences analysis of how students understand the Internet of Things and the different types of learning that can stem from allowing students to create their own smart, connected products. This section describes some of the early discoveries and inferences that we have made based on the design case presented in this paper. These thoughts do not come from a thorough research study but rather from one classroom case study and, therefore, only can suggest potential directions for a more comprehensive study.

Initial Insights from this Design Case

One important insight gathered from the first use case of the SymbIOTics system in a formal learning environment is that young students can, in fact, understand important IoT concepts such as internet connectivity and a network of connected devices. These concepts are somewhat abstract, and the lack of visible connection makes them challenging to visualize. However, through the use of the SymbIOTics system, students showed an understanding that all of the SymbIOTics hubs were connected to one network, which meant that they could access information from them. One of the most powerful learning opportunities presented by IoT technology is the ability to teach students that while they can build their own local systems that serve distinct purposes, their system will be limited by the resources they have in their possession. Through the use of internet-connected devices, students will be able to build more powerful systems that are no longer limited by the resources they possess but can incorporate all the information available on the internet. In the case of the SymbIOTics platform, students are limited if they use only their smart brick because they have one sensor and one actuator. However, when they were able to connect to their classmates' devices, they quickly realized that they could create much more powerful dashboards/systems. This was illustrated by the dashboards that students created with multiple rules and a plethora of sensors and actuators. Rather than just creating dashboards for the sensor/actuator they were given, students instead generated interfaces to control their classmates' devices in addition to their own.

Based on the quantitative and qualitative data collected from the student dashboards, there are several inferences that can be made about the learning happening with the SymbIOTics system. Initially, students had very little concept of what the internet was and how it could be used in applications other than a computer, cell phone, or gaming system. However, after interacting with the SymbIOTics system, they not only demonstrated an understanding of what a network of devices is, but also used that understanding to create their own internet-connected artifacts. Evidence of this understanding was obtained during the last class session, when students were asked to draw a schematic diagram of their LEGO zoo exhibit. Figure 12 shows two examples of student schematics.

In Figure 12a, the student drew an arrow between the smart brick and the computer labeled "goes all the way to Hong Kong." This is referring to the idea that the signal from the computer travels all the way to a server in Hong Kong, which then sends a signal to the Wio Node inside the smart brick. The lack of a physical connection between the computer and the smart brick depicted in this schematic further illustrates that this student recognized the wireless nature of how information was being transferred over the internet. In the schematic shown in Figure 12b, the student labeled the smart brick as being connected to the internet. The depiction of internet connectivity in these student schematics indicates student thinking about not only how the technology can be used, but also how it works on a technical level.

Future Research Goals

Having a class set of smart bricks in a SymbIOTics system all connected to the same internet network without individual security settings for each smart brick led to an important learning opportunity. As more and more students in the class started controlling each other's components, sometimes the actuator would perform in a way that the owner of that actuator didn't like because another student was controlling it. While this caused some initial confusion and frustration, it also sparked some valuable discussions about who could control the actuator. In one case, several students were controlling a DC motor, which was a water splasher built for the turtle exhibit. They decided as a group that they could all control the motor since the zookeeper would probably use only one dashboard at a time. Another pair of students had an argument about who could control the LED light strip. They ultimately decided that the owner of the actuator should get to control it. While seemingly not important, these conversations get at the important issue of security in IoT technologies. Beyond learning teamwork and compromise skills, students were also exposed to the challenges presented when devices are accessible via the internet.

Both the technical understanding and the peer-to-peer conversations that were observed in the pilot study were intriguing. The design team plans to conduct further research and analysis of these concepts to better understand how IoT could be leveraged in an educational setting, not only to teach students about technical concepts but also to investigate the types of collaboration and the engineering practices that students engage in while learning with IoT technology.

CONCLUSIONS AND NEXT STEPS

Conclusions

The SymbIOTics platform, or a system with similar components and structure, has potential for use in primary school classrooms as a tool to teach students fundamental concepts about the internet-connected technology that surrounds them. As smart, connected products continue to rise in popularity and importance, educational tools that facilitate learning with the Internet of Things will be in higher demand. Many of the current limitations of the SymbIOTics system could be solved through a more robust software system that incorporated both device management and device interaction from one interface. In addition, continued user testing in different types of classrooms and with different ages of students may present additional user needs not initially considered in this study. Furthermore, developing a curriculum centered around IoT systems and concepts will be an important step in more seamlessly integrating IoT technology into the classroom.

Next Steps

The next step for the design of the technology would be to revise the software system to have a more intuitive and robust interface that is accessible on tablet devices. This new software would add functionality so that users could set up and add devices without needing the Wio app. The revised software would also hopefully eliminate the need for firmware changes in order to change the sensor or actuator being used. Implementing and testing these additional features and other software changes will be important to better understand how students engage in the process of creating their own IoT devices.

The next steps for research will involve conducting further classroom studies with the improved technology. Observing and analyzing how students learn about, understand, and leverage the Internet of Things will help inform curriculum and future instructional technology design.

More information about the SymbIOTics system and ongoing research efforts can be found at: https://sites.google.com/site/symbioticsiotplatform/home

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