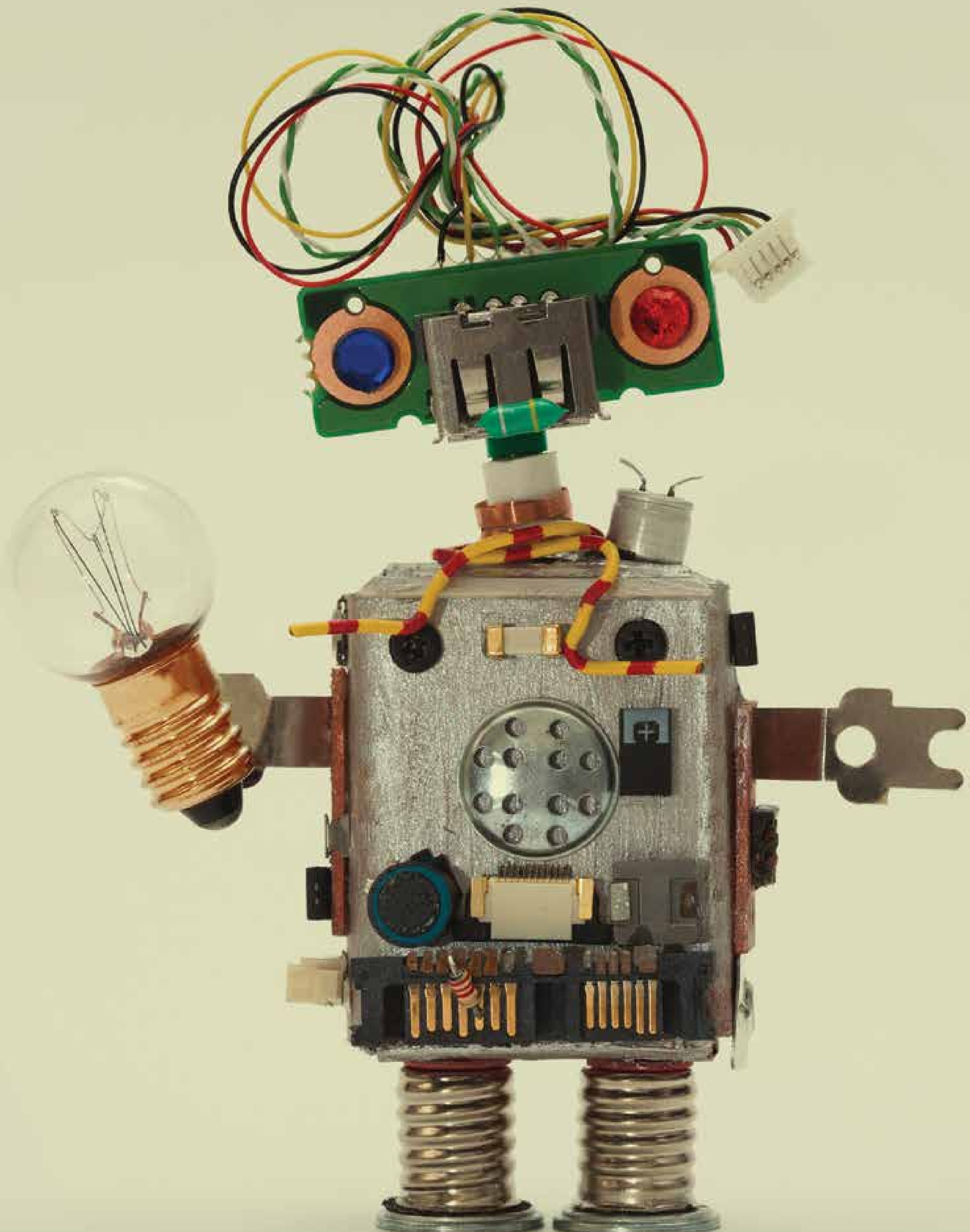


Building Bots to Develop Systems Thinking

BY NANCY B. SARDONE

CONTENT AREA

Engineering design

GRADE LEVEL

3–6

BIG IDEA/UNIT

Changes to the bot's subsystems affects how the overall bot system functions

ESSENTIAL PRE-EXISTING KNOWLEDGE

Students need to understand that batteries generate power/electricity. They need to be familiar with the notion of a system (e.g., solar system or the human body).

TIME REQUIRED

1 hour

COST

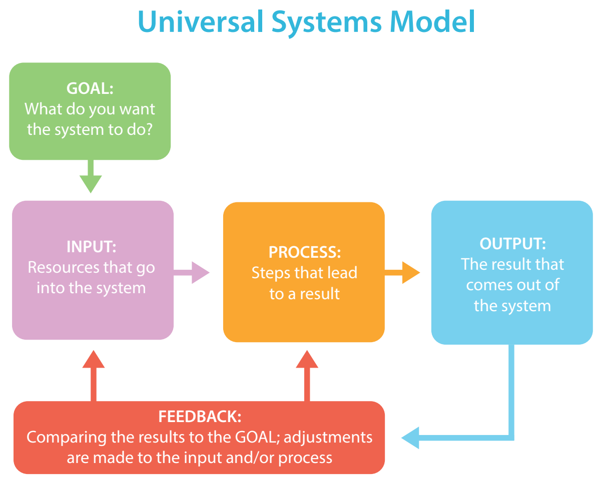
$5 per student ($150 for a class of 30)

Systems thinking is…? It seems like a simple enough question, right? Arnold and Wade (2015) state that the term has been a challenge to define and, as a result, has been pushed to the educational margins. Through evaluating long-standing, yet divergent definitions of systems thinking by researchers and authors from many disciplines, Arnold and Wade (2015) have redefined *systems thinking* as a set of analytic skills comprised of the ability to conceptualize, visualize, predict, articulate, solve, and devise modifications to produce desired effects.

Systems thinking is critical to success in a globalized and interconnected economy. In *The Teaching of Science: 21st-century Perspectives*, Roger Bybee (2010) further defines systems thinking as the ability to understand how an entire system works, and how an action, change, or malfunction in one part of the system affects the rest of the system—adopting a "big picture" perspective on work. Further, such thinking processes include judgment and decision making, systems analysis, and evaluation, as well as abstract reasoning about how the different elements of a work process interact. In essence, systems thinking is an analytic process skill used to solve problems. This type of thinking can be developed through hands-on exploration by analyzing the interconnectedness of system components to find meaning. Whereas traditional analysis focuses on separating the individual pieces of what is being studied into constituent parts, systems thinking, in contrast, focuses on how the thing being studied interacts with the other constituents of the system—a set of elements that interact to produce behavior (Aronson 1998).

This article describes a hands-on activity in which students build a scribble bot and determine how each part functions to form a system. Through modifications to meet the stated goal and subsequent challenges, students determine how a change in the subsystem of a bot affects how that system functions, helping to develop their systems thinking.

FIGURE 1: Universal systems model



Sequence of instruction

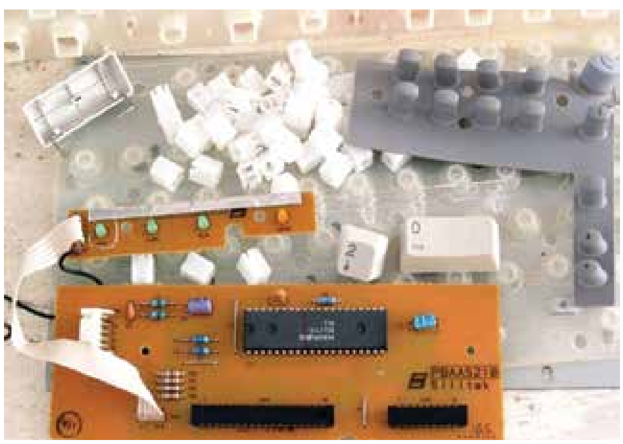
Students need to have prior experiences with batteries before this bot-building activity. As a refresher on how batteries operate, the teacher could use the free app "How to Make Electricity" or visit "Power Systems" (see Resources) to help students remember how batteries generate electricity.

In a whole-group discussion, the teacher can discuss the universal system model as a method to describe how a system works and how to analyze a system (see Figure 1). According to the universal systems model, all systems have a common set of elements: a goal or need, input, process, output, and feedback.

The teacher provides examples of three different types of systems: natural, human-made, and engineered. An example of a natural system is the solar system consisting of a central star, the Sun, and all of the smaller celestial bodies that continuously travel around it. These smaller bodies include eight planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune, orbited by more than 140 moons. The solar system contains millions of rocky asteroids and billions of icy comets. All of these objects are held together in a group by the Sun's gravity (NASA 2016).

An example of a human-made system is the U.S. public education system, consisting of the federal government as the central funding body; state governments who set educational standards and standardized testing; local school boards who oversee curricula, budgets, and policies; and schools. Schools include elementary, secondary, and postsecondary levels and students are divided by age into grades, ranging from kindergarten and first grade for the

FIGURE 2: Dissected computer keyboard



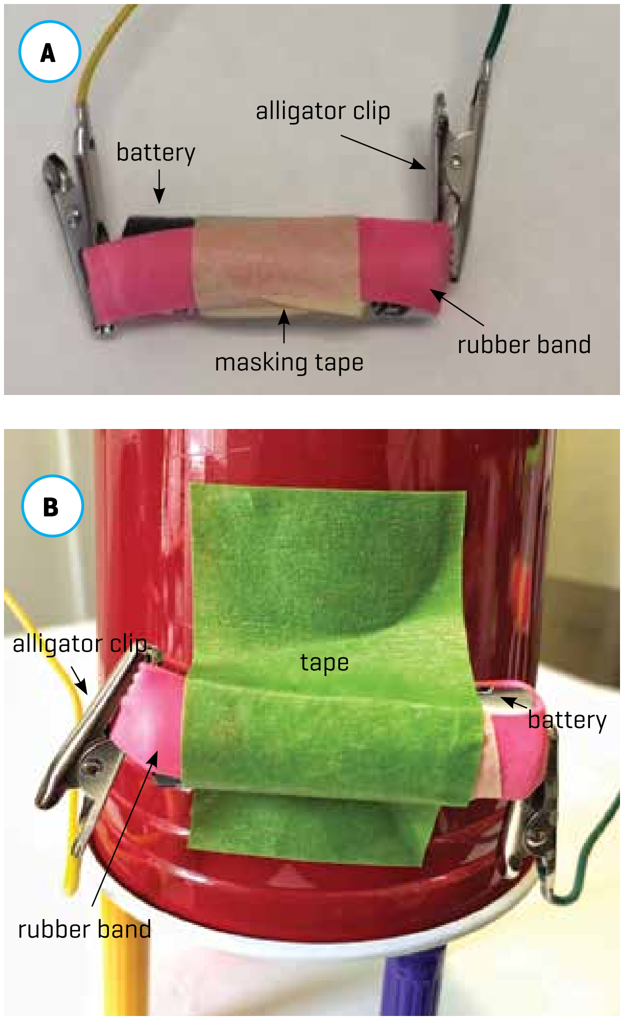
youngest children, up to twelfth grade as the final year of high school.

Referring to the universal system model (Figure 1), the teacher could ask students the following questions about the U.S. school system:

1. Goal or need: What is the goal for schools? (Expected answers include: to educate students, to help students learn important information to help them in their future careers.)
2. Input: What are the resources that go into a school system? (Expected answers are: buildings, furniture, students, parents, teachers, administrators, curricula, instructional materials, and transportation means.)
3. Process: What are the steps that lead to the result/goal? (Expected answers are: students attend school from August/September until May/June of each year with some vacation time built in. Students are taught lessons by qualified teachers according to specified curricula.)
4. Output: What is the result that comes out of the system? (Expected answers are students receive a diploma and students are prepared for their next level of education or a career.)
5. Feedback: Compare the results to the goal or need. How might the results differ from the goals? (Expected answers are: students can provide valuable information such as which courses they found helpful in finding an area of interest they wish to pursue in college or in their careers; or students can offer ideas for which projects they found difficult or concepts they found difficult to understand.)

Another example of a system is the U.S. Highway system, an engineered system that is a network of interconnected state, U.S., and interstate highways. Generally, north-to-south highways are odd-numbered, with lowest numbers in the east, the area of the founding 13 states, and highest numbers found in the western states. Highways running east to west are typically even-numbered, with the lowest numbers in the North, where roads were first improved

FIGURE 3: Creating the battery assembly



most intensively, with highest numbers found in the southern United States.

With Figure 1 projected, students are given a worksheet (see “Computer Assembly Plant” in the Online Supplemental Materials), which asks them to apply the universal systems model to a specific engineered system (computer assembly plant). This task asks students to explain how engineers use the universal systems model in their work on systems that involve assembly.

The teacher could then discuss subsystems as a smaller system of the larger one. The discussion might begin with a computer component as an example of a subsystem: a standard QWERTY computer keyboard. You could start with Figure 2, and ask students to write answers to these questions:

- *Can you identify the item in this picture?* (computer keyboard)
- *Can you name some of the parts found in the image?* (circuit board, plungers, keys, ribbon cables, ribbon connectors, shell, LEDs, resistors)
- *Can you state the larger system in which the keyboard is used?* (computer system)
- *Based on what you see and know about a computer keyboard, which part do you think is the most important part of this subsystem operation?* (Students might answer the keys, but the answer is the switch underneath each key).

The teacher could bring out an actual dissected keyboard and review vocabulary terms (i.e., circuit board, LEDs, plungers, ribbon cable, switches, and transistors), each representing additional subsystems. The discussion should center on the interconnectedness of the keyboard parts (i.e., circuit board, plungers, keys, ribbon cables, ribbon connectors, shell, LEDs, resistors) to form the whole of the keyboard as a subsystem of the larger system, the computer. The keyboard in and of itself, is a system comprised of its own subsystem.

With the computer system powered off, students could be asked if they could tell if a computer keyboard was malfunctioning by looking at it. The teacher can point out that you can't really tell if a computer keyboard is malfunctioning if it is not turned on and connected to the larger computer system. Therefore, the keyboard is virtually useless without the computer system, and the computer system is useless without the keyboard as its input device. They are interconnected parts in a system.

Bot building

The idea for the bot-building activity can be found in the book *The Art of Tinkering* (Wilkinson and Petrich 2013). To get students ready for the bot-building activity, it is a good idea to explain what a scribble bot is and show an example of a completed bot. A *scribble bot* is a motorized contraption or mini-robot that moves in unusual ways and leaves a mark to trace its path. Each bot can be customized with different colored markers and different types of bodies (i.e., plastic cups, empty strawberry baskets, Styrofoam cups). Depending on the number of markers and the type or weight of the body used, the bot will move and draw differently.

FIGURE 4: Markers taped to cup

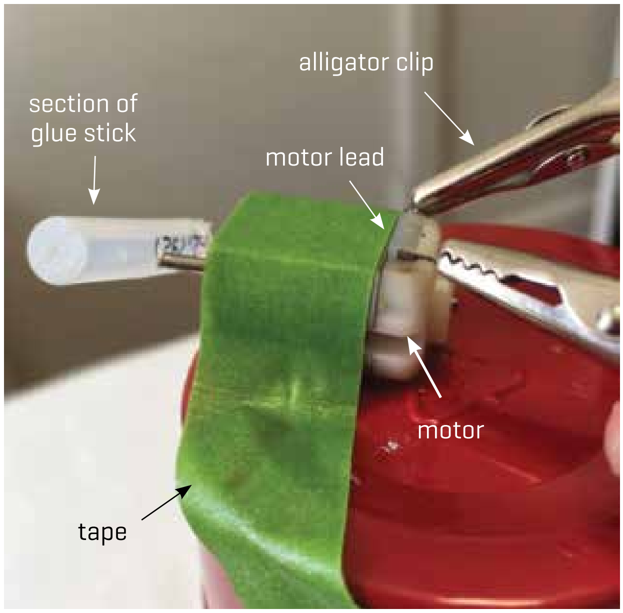
Materials

Supplies include markers (varied sizes and colors), butcher block–type paper taped to the floor, paper taped to large tables, AA batteries, plastic cups of all sizes or weights, 130 size DC hobby motors, rubber bands, small alligator clip test leads, tape, decorations, and assorted items to be used to attach to the motor's shaft. To begin construction of your bot, place a rubber band around the battery and then add tape around the battery and rubber band to hold it them together. Connect the alligator clips to the rubber band at either end of the battery so the clips make contact with positive and negative terminals (Figure 3a). Tape the battery assembly to the cup (Figure 3b). Tape the markers to the cup, but don't remove the caps (Figure 4). Next, attach a propeller to the shaft of the motor, and then tape the motor to the top of the cup. Make sure that you choose a location for the motor that allows the propeller to spin freely without hitting the cup. Figure 5 shows a small section of glue stick being used as a propeller, but you can provide a variety of objects for students to experiment with as propellers. Attach the alligator clips to the leads on the motor. Once attached, the motor should start, the propeller should start spinning, and the cup will start to move. Remove the alligator clips and move the bot to a large piece of butcher block paper. When ready to test the bot, remove the marker caps and reattach the alligator clips. The bot will make its way across the paper.

Before asking students to engage in the bot build, I recommend that teachers build their own bot, keeping in mind a few key design notes. The bots tend to move in a circle, leaving a trail of dots in their wake. The challenge is to get the bot to move across the paper, a much harder task. This requires a discussion with students about systems thinking. It should include the following:

- Understanding constraints and criteria (i.e., the goal is to get bot to move; the challenge is to make the bot draw straight lines versus curved lines)
- Developing creative solutions (i.e., consider the weight of the object attached to the motor's shaft, the weight of the plastic cup used, the total number of and thickness of the markers used, the amount of tape used to hold the battery to the cup)
- Considering the subsystem's effect on other subsystems (i.e., placement of the battery on the cup will affect the weight distribution and the overall functioning of the bot; the life cycle of the battery is limited)

FIGURE 5: The battery assembly on the cup



Instructions for students

Safety procedures and materials for the bot build need to be reviewed with students, as follows:

- Safety goggles must be worn during the construction and testing of the bot.
- Paper must be taped down to the table so scribble marks won't show on the table.
- Do not let the red and black wires of the motor touch each other.
- A battery is a compact, transportable source of electricity with chemical substances that react together to separate positive and negative charges. Batteries are not toys.
  Remember: When a battery is connected in a circuit, it provides the energy that drives the electrons along in a current.

Each student should collect their materials from a table:

- 1 large piece of paper taped to table
- 1 AA battery
- 1 motor

FIGURE 6: Battle of the bots

- 1 plastic cup
- 3–5 markers
- 1 roll of tape
- 2 alligator clip wires
- 1 rubber band
- 1–3 items to attach to the motor's shaft, acting as the propeller

Goal: Build a scribble bot using the available materials and get it to move in any direction, in a teacher-given amount of time.

Challenges: Get your bot to move across the provided paper in a straight line; get you bot to move in a circular direction.

Students need to work for approximately 40 minutes to build their bots. They may all start the same way by taping the markers to the cup; some may tape markers inside the cup (harder to do), while others might attach the markers to the outside of the cup. Some students may work to make the markers even on the cup, not realizing that this design is more apt to lead to the circular rotation of the cup. They may reach the goal and challenge without realizing what they did. In this instance, students need to study the designs of others to meet the other goal—to move in a straight line across the paper. Expect the first bots to be moving within 15–20 minutes. Students should be encouraged to test their bots as they build them. I suggest providing large poster paper taped to the floor for bot testing purposes (Figure 6).

Students may ask about the different items to attach to the motor's shaft. Some may struggle to attach the small cut-up pieces of available supplies to the shaft. Provide craft supplies for decorating bots (i.e., googly eyes, pom-poms, pipe cleaners, stick-on mustaches) after both the challenges are met. After 60 minutes or so, the teacher can expect the majority of bots to be assembled (see Figure 6). Teachers may need to find a natural stopping point if their class is shorter than the allotted time. I suggest two class sessions: one dedicated to bot building and another for testing.

While watching their bot move, students will begin to recognize problems with their bot. The teacher may choose to prompt students with the following questions for consideration or wait until a student asks a question:

- Is your battery placement making your bot lopsided?
- How might the bot's markings change if the position of the battery was altered?
- How might the weight of the object sitting on the shaft affect the overall function of your bot's system?
- How might the bot's markings change if the weight of the object on the shaft was altered?

FIGURE 7: Completed scribble bot

- How does the weight of your cup affect the overall function of your bot system?
- How might the bot's markings change if you used a different cup?
- How many markers are you using in your system compared to another bot system?
- How might the bot's markings change if the number of markers used was altered?

Students should be expected to use information or data collected to refine their system. For example, after prompting or on their own, some students may notice that their bot moves slower compared to other bot designs and may ask for a new battery. Others may remove markers after observing that their bot moved in a different direction compared to other bots. Other students may consult with one another on their builds while others may work alone. The teacher's bot model should be made available to students who prefer to work alone. When refining their bots, students may move in and out of their original groups to pursue learning in smaller groups or individually.

Students should be allowed to return to the large paper arena when they feel their refinements are ready for retesting to meet the challenges provided. They will continue to analyze data through observations to determine the similarities and differences among several design solutions to identify the best characteristics of each that could be combined into a new solution to meet the challenges.

The teacher could decide on a new measure such as "plough through" (the bot that ploughs through two, three, or four other bots) and have students engage in "Battle of the Bots" once all bots have met the assignment goals and challenges. I suggest that the teacher show students their bot, explain the building process, and then allow students to work at their own pace to build and test their bots. As students complete their bots, they can bring the bot to the test area—the butcher-block paper on the floor.

Differentiation

This activity is easily differentiated for students, following the strategy laid out by Tomlinson (2001) to include product, process, and content differentiation. Product differentiation might ask students with special needs to build a bot and make it move, accepting any movement as meeting project criteria, whereas for older or gifted students, you might ask them to alter or rebuild the bot based on criteria that are more sophisticated (i.e., move faster, move in a specified direction, move with a specified number of markers).

Similar to content differentiation, process differentiation is based on student readiness, matching the complexity of a task to a student's current level of understanding and skill. Process differentiation might provide students with options as to where they construct their bot (i.e., sitting on the floor, sitting at a straight chair while working at a waist-high table, or standing at a taller table). It might mean that the activity varies in its allot-

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

- The chart below makes one set of connections between the instruction outlined in this article and the *NGSS*. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities.
- The materials, lessons, and activities outlined in the article are just one step toward reaching the performance expectations listed below.

Standard

MS-ETS1: Engineering Design
www.nextgenscience.org/dci-arrangement/ms-ets1-engineering-design

Performance Expectation

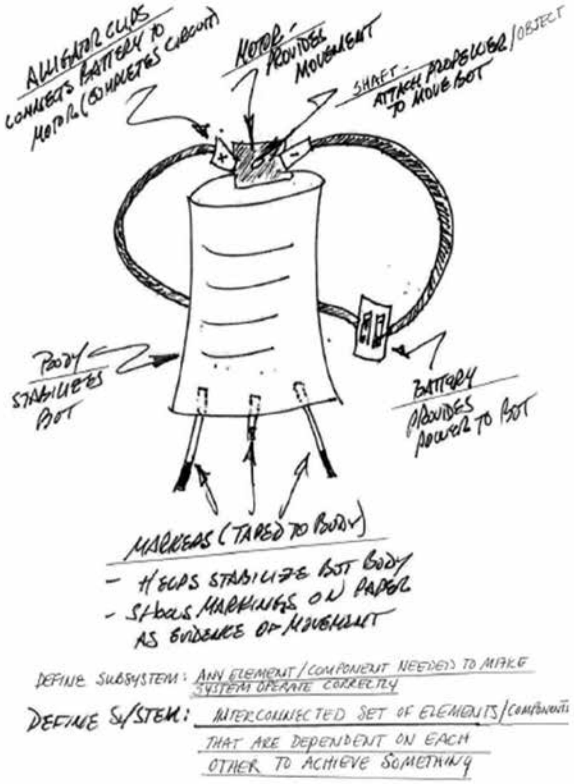
MS-ETS1-4: Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

DIMENSIONS	CLASSROOM CONNECTIONS
Science and Engineering Practice	
Analyzing and Interpreting Data	Students observe the markings on paper during Battle of the Bots to determine how to improve the movement of their bot to meet the challenge.
Disciplinary Core Idea	
ETS1.B: Developing a Possible Solution • A solution needs to be tested, and then modified on the basis of the test results, in order to improve it.	Students refine their bots to improve their bot's performance after considering the following questions: How might the bot's markings change if the number of markers used was altered? How might the bot's markings change if the position of the battery was altered? How might the bot's markings change if the battery was changed? How might the bot's markings change if the weight of the cup used was altered?
Crosscutting Concept	
Systems and System Models	Students identify the system components of a computer assembly plant. Students identify the parts of a computer keyboard as a subset of a computer. Students build a model of a bot and then refine their model to meet a specific criteria

ted time span, where some students might want to work on their bot at home or after school. In addition, offering varied amounts of teacher or peer support is a good idea for those students who may be struggling. Another idea is the option of working alone versus with a partner.

Differentiating content could involve adapting or modifying the materials students are given. For example, some students might respond better to receiving a half-completed bot or one that at least has its colored markers already taped to the body.

FIGURE 8: Scribble bot diagram



Summative assessment

Summative assessment ideas include the following: asking students to highlight some common traits of effective systems, identifying some of the systems that help ensure the safety of students at their school, applying the universal systems model to the bot system, or perhaps creating a systems diagram of their scribble bot.

See Figure 8 for an example of how students might demonstrate their knowledge of a system. Students can draw a systems diagram of their bot, label each part, and explain the function of each part. Students in need of assessment differentiation might benefit from the inclusion of a word bank to help them fill in the correct terms or definitions.

Conclusion

Investigating how parts form the whole using student-centered strategies is important in developing systems thinking. This hands-on exploration provides students with the required backdrop to develop systems thinking. Students determine why their bot tended to move in circles and then challenged to make alterations to move it across the paper. Although it might appear on the surface that students' success was measured by achieving the challenge of a straight-line movement of the bot rather than the understanding of a system, they could not have met the challenge without considering the individual subsystem components (i.e., is the battery dead? Is the alligator clip in the right place on the battery? Do I have too many markers? Is the weight unbalanced?) and its impact on the system. ●

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RESOURCES

How to make electricity app—*http://crayonfriends.com/electricity*

NGSS Appendix G: Crosscutting Concepts—*http://bit.ly/2e16r40*

NGSS Appendix H: Nature of Science—*http://bit.ly/2dadqco*

NGSS Appendix I: Engineering Design—*http://bit.ly/2ebmycJ*

Power systems—*http://bit.ly/2e0Yihk*

ONLINE SUPPLEMENTAL MATERIALS

Computer assembly plant—*www.nsta.org/scope1701*

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