Developing a Systems Engineering Activity for Middle School Students Using LEGO Robotics

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Introduction

Formal education in systems engineering (SE) has grown precipitously in recent decades. The number of higher education institutions with related academic programs in the U.S. has increased from 30 in 2000[1] to 48 in 2005,[2] 69 in 2010,[3] and as many as 282 (including both systems engineering and industrial engineering programs) in 2016[4]. SE education emphasizes teamwork and communication skills and a takes broad perspective on engineering to integrate knowledge across multiple disciplines.[5,6]

SE academic programs have traditionally focused on master's degrees and continuing education programs to meet industry and government needs.[7] Undergraduate SE education is somewhat controversial because of the beliefs of some practitioners that engineers must develop expertise in a single domain before addressing systems topics.[8] This perspective is linked to the current model where a bachelor's degree in engineering signals an individual to be ready for the workplace, in contrast to other professional degrees such as law, medicine, or business.[9]

Broader calls for transformation in engineering education promote holistic concepts beyond math and science to formulate and solve complex societal challenges[10] and combine mastery of technical fundamentals with practical design in a meaningful context[11]. Significant effort has been put into emphasizing design experience in problem- or project-based learning for undergraduates[12,13] including SE concepts and systems thinking[14] and complex socio-technical systems[15,16].

These recent efforts at the university level align with K-12 initiatives to promote science, technology, engineering, and mathematics[17] and understand daily experiences with engineering artifacts.[18] Indeed, the U.S. National Research Council's framework for K-12 science education distinguishes engineering practices and includes core ideas in engineering design.[19] SE topics, in particular, provide an interdisciplinary opportunity to design and build while also considering tradeoffs in a collaborative activity.[20] Knowledge of SE is also important for students' technological literacy, enabling them to understand how all the components of a system—technological, human, and natural—affect the others in positive and negative ways. In Sweden, technical and social-technical systems are part of the compulsory curriculum.[21] In the U.S., the International Technology Educators Association's second Standard for Technological Literacy is that students can recognize the core concepts of technology. [22] This includes specific learning objectives about systems engineering for each grade level: for example, 6th-8th grade students should learn that "systems thinking involves considering how every part relates to others," and "requirements are the parameters placed on the development of a product or system" (p. 39).

Some organizations have developed and executed SE-oriented K-12 outreach and educational programs.[20,23] Despite this interest, few studies have been able to assesses outcomes. Jain et al.[24,25] use multiple-choice pre- and post-tests to assess student learning on three levels: 1) SE information content, 2) SE applications, and 3) analysis of SE concepts. Results show a statistically significant increase in post-test scores for levels 1 and 2; however, they employ an imperfect instrument to measure SE knowledge. Other studies, including Bartus and Fisher[23], provide qualitative descriptions of experiences for students or teachers involved in SE activities.

K-12 Systems Engineering Learning Objectives

Our work draws from the motivation of project-based learning to have K-12 students learn about systems engineering (SE) in a hands-on design activity. Similar to Erwin[20] and Bartus and Fisher[23], it structures an activity as a variant of the SE process to define objectives and requirements; decompose, implement, and integrate subsystems; verify requirements and validate objectives; and finally operate the system. We identify three learning objectives for the K-12 audience in this activity:

1. *A system can be decomposed into subsystems*. This learning objective nurtures students' ability to perform systems thinking by viewing an entity as a set of interrelated components. Decomposing a system into its constituent subsystems also assigns functional attributes to alternative physical forms in the architecting process.
2. *Designers coordinate activities by communicating requirements and interfaces*. This learning objective introduces the primary mechanisms in SE to communicate information between designers: requirements and interface control documents. Requirements flow systems objectives down to lower levels and enforce constraints imposed by architectural decisions. Interfaces, a more specific type of requirement, define how subsystems connect to each other with physical, energy, fluid, or information links.
3. *Testing reveals problems and changes propagate to other components*. This learning objective emphasizes the iterative process sometimes required in systems design to resolve communication interdependencies between designers. It highlights how incorrect or incomplete requirements can cause problems in systems design, testing as a part of a larger verification and validation plan can uncover problems, and how design changes have a tendency to propagate between subsystems.

These topics expose fundamental parts of the SE process[26] but also align with broader objectives in engineering education[27] to view design as a multidisciplinary activity where designers must effectively work in teams to meet conflicting objectives.

To allow students to experience these learning objectives firsthand, we developed an interactive workshop activity for middle school students using LEGO EV3 robotics. Students were challenged to design a "toxic waste disposal robot" that would pick up a container of "toxic waste" (a soda can) and deposit it inside a "safe disposal container." These robots were constructed of multiple subsystems that had to function together to complete the challenge.

The development of this SE activity took place over seven months, and included five workshops with middle school students held at the Tufts University Center for Engineering Education and Outreach. We spent the summer and fall of 2015 developing the first iteration of our activity, making minor adjustments both times we piloted the activity with students. We ultimately decided the first iteration was unsuccessful on multiple levels—namely, the challenge was too difficult and kept students from connecting the SE learning objectives to the activity. As a result, we made large changes in the second iteration of the activity. We organized three additional workshops in January 2016, and found that students were much more successful in completing the challenge and gaining an understanding of the learning objectives.

In the following sections we describe the two iterations of our activity, focusing on the successes and challenges of each iteration. By presenting our development process, rather than simply showing the final activity, we seek to emphasize important considerations for anyone developing a SE activity for K-12 students. We conclude this paper by presenting an initial qualitative assessment of students' learning from full-group discussions in the January workshops.

First Iteration of the Systems Engineering Activity

Description of the Activity

The first iteration of our activity assigned six students to work together as a team to design and build one toxic waste disposal robot from the ground up. In general, the robot was required to travel a particular distance, grab a soda can (representing the "toxic waste"), and move the can into a box or taped-off area representing a "safe disposal container." The six students were divided into three teams of two, with each team responsible for one subsystem of the robot: the arm, the chassis, or the programming. The arm team was responsible for creating the robot's gripping mechanism, which would be able to pick up the can and place it in the disposal container. The chassis team was responsible for developing a structure that 1) allowed the robot to move from place to place, 2) provided attachment points for the EV3 Intelligent Brick (the computer) and the arm, and 3) supported the weight of the Intelligent Brick, the arm, and the can. The programming team was the only team that was given the Intelligent Brick, and was responsible for writing the robot's program and determining what sensor to use.

The specific challenge varied slightly for the two pilot workshops we ran. In the first pilot, the robot had to travel forward 55 inches, grab the can and lift it at least 5 inches off the ground, travel forward another 55 inches, deposit the can into a container, and then return to the starting line (Figure 1). During the pilot, students working on the arm subsystem had trouble designing and building an arm that could open and close and move up and down. As a result, we simplified the arm's requirements for the second pilot. Here, the robot had to travel 50 inches, grab the can off an elevated platform 3 inches tall, pivot 90 degrees to the right, and deposit the can into a taped-off area on the table (Figure 2). In this challenge, the arm only had to open and close; it did not need to move up and down. The programming requirements were correspondingly simpler in this second pilot.

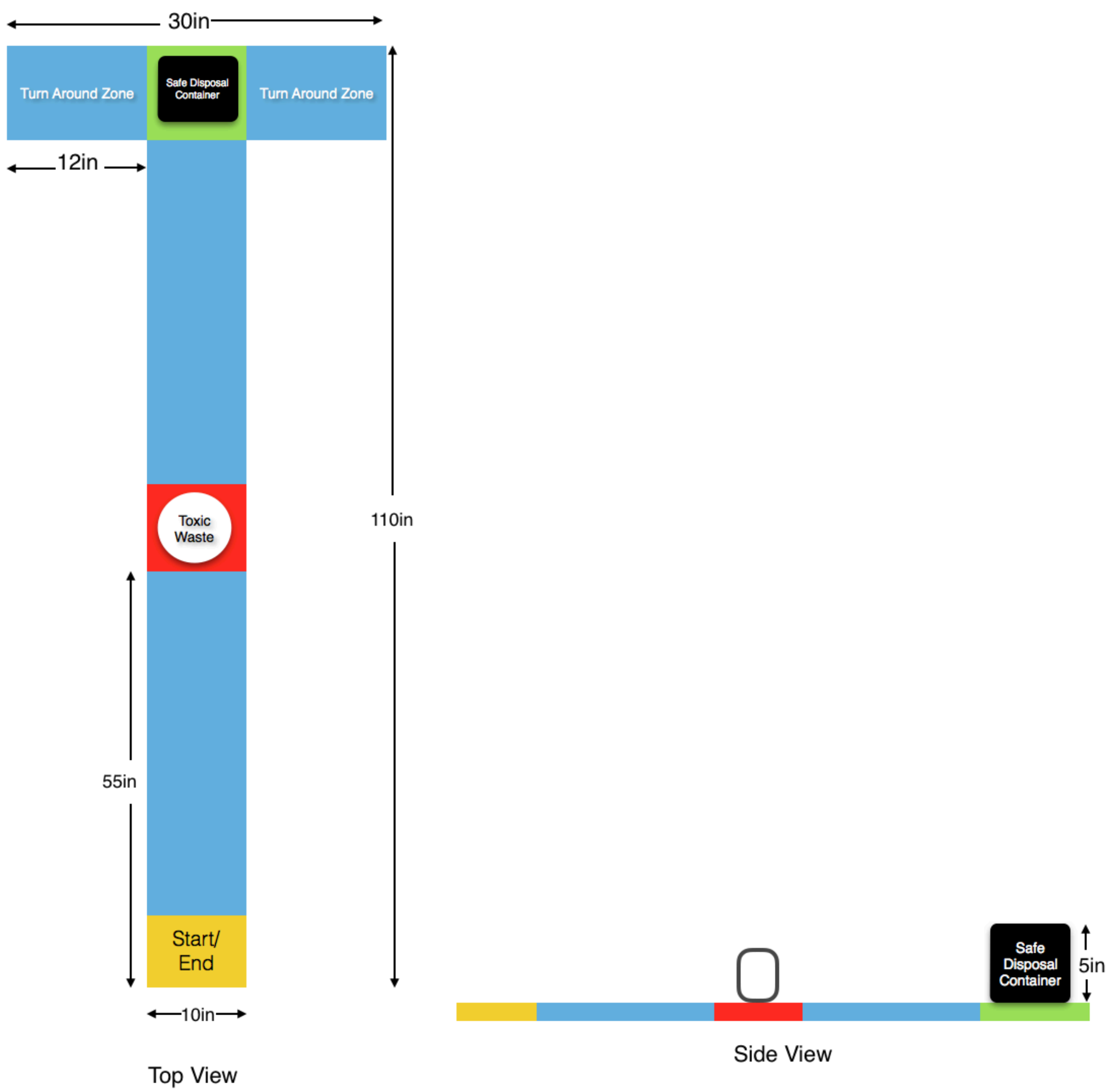

Figure 1: Diagram of the challenge given to students in the first pilot of our systems engineering workshop.

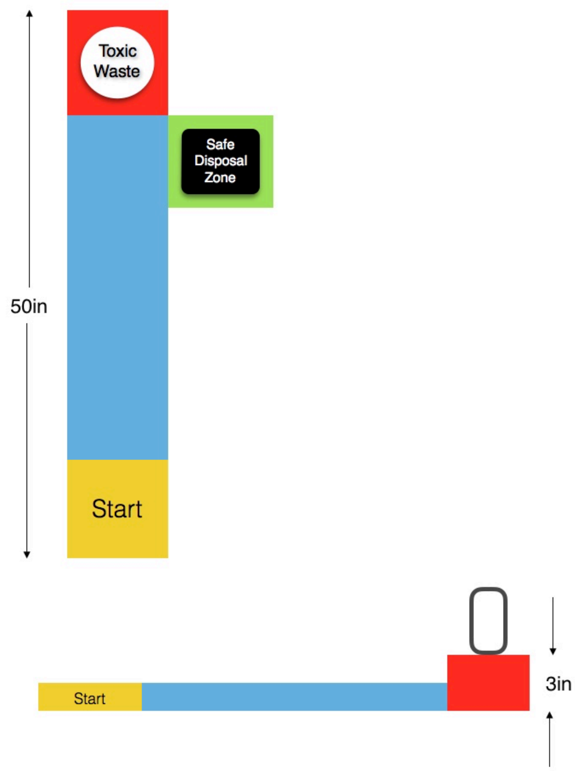

Figure 2. Diagram of the challenge given to students in the second pilot of our systems engineering workshop.

Each subsystem team was assigned a different area of the room in which to work. Students were allowed to collaborate with other teams at the center table, but could not bring their LEGO pieces to show one another. As a result, students were required to describe their subsystems through words or drawings. We provided students with a requirements document in the form of a triple Venn diagram. Students were encouraged to make collaborative design decisions and then write the resulting subsystem and interface requirements on this Venn diagram. We believed this admittedly artificial constraint would encourage students to communicate across subsystem teams and emphasize the need for clear documentation and requirements. We hoped students would continually update the requirements document, thereby providing a reference for each team to follow as they built or programmed their subsystem. Our concern was if students all worked at the same table and could freely see the other teams' constructions, there would be no need to document the evolving requirements As a result, we worried our second learning objective (designers coordinate activities by communicating requirements and interfaces) would not be achieved.

Evaluation of the Activity

We were encouraged by the students' actions and behaviors during the first iteration of the activity. The students worked well together, despite not knowing each other before the workshop. Before allowing the teams to start building their subsystems, we facilitated a discussion with all students to make some initial design decisions. Each student was given five minutes to design a robot on their own that would complete the task, and then students shared their ideas with the whole group. The students respected each other's ideas, and were able to come to a consensus on a number of design decisions—for example, what sensor to use to tell the robot that it needed to stop and grab the can.

Students also discovered a number of missing requirements as they worked in teams to design and build their subsystems. For example, the programming team needed to know how long the arm was going to be in order to program the robot to stop at a particular distance from the can. Or, the chassis team needed to know more details about the arm design in order to ensure that it could be connected to the robot's body. In some cases the students asked another team for this information on their own accord, and in other cases we had to facilitate these discussions. However, we were encouraged by seeing students identify a need to set functional and interface requirements to successfully complete their subsystem design and have it work with the other subsystems.

While there were a number of encouraging student behaviors in the first iteration of our systems engineering activity, the challenge we developed was too difficult for the students. We had hoped that students would have multiple chances to integrate and test the entire robot, but the students in both pilot workshops failed to successfully integrate their robot even once despite having workshops that were 2.5 and 3 hours long (first and second pilot, respectively). We believe this occurred because the challenge simply had too many functional and interface requirements. For example, students found it difficult to build an arm with two degrees of freedom (opening/closing and moving up/down) on its own, let alone build it while ensuring that it could interface with software and a chassis.

The chassis team in the second pilot also had difficulty building their subsystem. Their subsystem design relied heavily on decisions made by the other teams, and small lapses in communication lead to large frustrations. While students identified some requirements that needed to be communicated across teams, they failed to recognize a larger number. This is indicated by how students in both pilot workshops did not use the Venn diagram to specify requirements as we had scaffolded earlier in the workshop. In the first pilot, the diagram was drawn on a whiteboard in the corner of the room, away from where the students were working. We thought that this placement influenced the diagram's disuse, and so we placed it on the central table in the second pilot. However, students still neglected this requirements document. Students told us that they did not believe it was important, and that they could communicate all requirements verbally. When students brought their subsystems together for the first (and only) integration, it was clear that there was a large number of interface requirements that were not discussed and therefore causing issues. Had the workshop lasted longer, we may have been able to use this experience to encourage students to record requirements on the Venn diagram.

However, we did not want to lengthen the activity because a number of students were already tired and displaying fading interest by the end of the 2.5- or 3-hour workshop.

Another challenge of this first iteration of our activity was ensuring that each subsystem was the same difficulty to construct. In both pilots, we would occasionally poll the teams as to how complete their design was. It was not uncommon to have one team nearly finished while one team felt less than half done. Lastly, we found some students felt more comfortable than others with the LEGO EV3 sets. We had asked students attending the workshops to have experience with LEGO EV3, but we had no way of assessing experience beyond a simple survey given at the beginning of the workshop.

Second Iteration of the Systems Engineering Activity

Description of the Activity

After the first iteration of our systems engineering (SE) activity, we spent the month of December redesigning the activity. We kept the toxic waste disposal theme and general challenge, but changed what students were asked to build. Having students design and build subsystems from scratch caused many of the challenges in the first iteration, and upon reflection we felt it did not strongly promote our learning objectives. We were not interested in how students designed subsystems, but how they integrated subsystems together. This motivated the largest change in the second iteration of our activity: we provided students with a pre-built arm and chassis, and pre-programmed the EV3 Intelligent Brick.

In the second iteration of the SE activity, the robot was required to drive forward 50 inches, grab the soda can off a platform, and place it in a disposal zone. In the third pilot workshop (for eight 3^{rd}-5^{th} grade students), the disposal zone was off to the left of the platform. However, we determined that this 90 degree turn was unnecessary and moved the disposal zone to the place where the robot started from. Figure 3 shows the design of the challenge for our fourth and fifth workshops, which we refer to as our “data collection workshops” as we collected video and photographic data of the students for later analysis. This procedure was approved by the Tufts University Institutional Review Board.

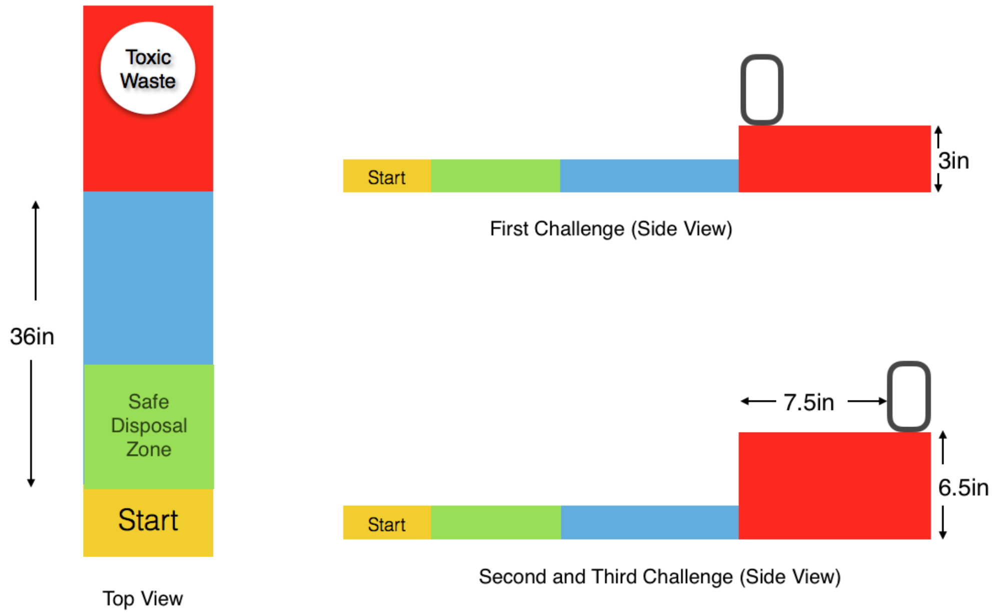

Figure 3: Diagram of the challenge given to students in our January 2016 "data collection" systems engineering workshops.

In the data collection workshops, the robot traveled 36 inches between the start line and the platform, and picked up an empty soda can off the front of a 3-inch tall platform. It then traveled backwards to the start line and released the can. After students completed this challenge, we had two additional challenges of increasing difficulty. First, we placed the empty can 7.5 inches back from the edge of a new platform that was 6.5 inches tall. This required students to modify their arm to be longer and taller. Second, we filled the empty can with 35 pennies, creating a larger tipping moment on the robot. These additional challenges highlighted the importance of our SE learning objectives. The changes students had to make to the arm necessitated changes to the interface to stabilize the arm, and to the chassis to prevent the larger arm and heavier can from tipping the robot over. We believed this would give students experience with the interdependency between subsystems inherent in a system.

Eleven middle-school students participated in the first data collection workshop, and ten middle-school students participated in the second. Four of the twenty-one participants had participated in the pilot workshops during the first iteration of the activity. Each data collection workshop lasted two hours, and began with a presentation introducing systems engineering developed by the third author. This presentation covered a brief history and definition of systems engineering, and used the NASA Space Transportation System (STS) as an example to show how systems can be broken down at multiple levels into component parts.[26] Finally, this presentation discussed functional and interface requirements within the STS example.

After this presentation, students had approximately 90 minutes to complete the challenges. Students were paired off and given a pre-constructed chassis and arm (Figure 4). Students were also given an iPad to document their building process, and video cameras around the room captured the students working and testing their robots. We took a number of steps to encourage students to make informed design decisions instead of making random choices and testing frequently. We suggested students bring their partially-constructed robots up to the test setup (Figure 5) to gather feedback, and challenged students to successfully complete the task the first time they ran their robot. We also provided tape lines that helped students to estimate where their robots would stop.

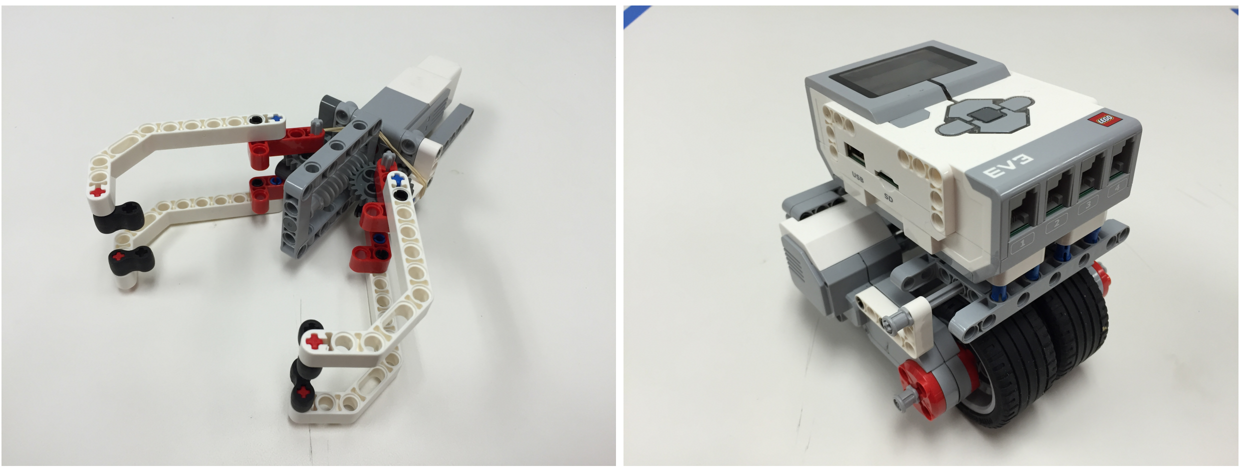

Figure 4: The pre-built EV3 arm (left) and chassis (right) provided to students in the second iteration of our systems engineering activity.

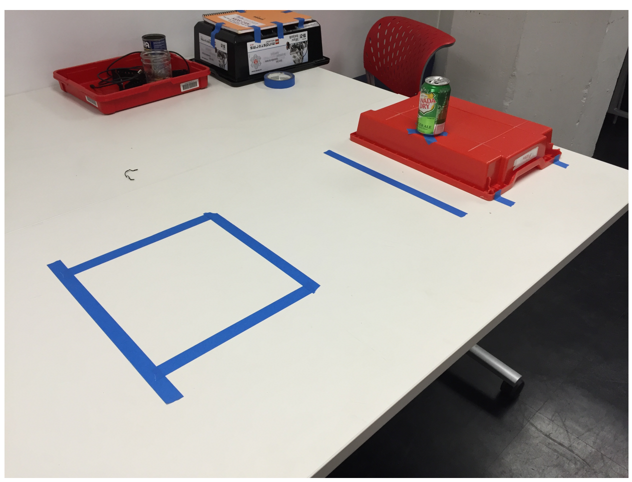

Figure 5: Test setup for the first challenge in the second iteration of our systems engineering activity. The green soda can represents the "toxic waste," and the blue tape square represents the "safe disposal zone." The other taped lines are guides that helped students to estimate where their robot would stop in relation to the red platform.

Evaluation of the Activity

This second iteration of the SE activity was much more successful than the first iteration. All groups were able to accomplish the first challenge of retrieving the empty soda can from the low platform. Many of these were successful on the first try, indicating that students were making informed design decisions. Also confirming this is our observation that most, if not all, groups brought their partially-completed robots up to the test setup multiple times. Most groups, but not all, were also able to accomplish the second challenge of retrieving the empty can from the high platform. Students also made informed design decisions on this challenge, continuing to frequently check their partially-completed robots against the new test setup. We also observed students having detailed and thoughtful discussions with their partners. As intended, they considered the changes that they needed to make to their arm and the interface.

Only three groups out of eleven were able to accomplish the third challenge of retrieving the heavy soda can from the high platform, and none were successful on the first try. Some of these failures were due to issues with the arm design we provided students, which did not always successfully close around the heavy can. This is one area we plan to improve upon in future iterations of the workshop. Other failures were due to the weight of the can, and the robot tipped over as we expected. Students who were successful at this challenge modified their chassis to counteract the weight of the can. In future workshops we plan to modify this third challenge further to incrementally increase the number of pennies in the can by 5 or 10. The finer granularity will give students a better idea of how their robot performs, rather than one pass/fail assessment with 35 pennies.

The fact that students were successful at all three challenges within the 90-minute build time tells us that the challenge was the right level of difficulty. It could be accomplished, but not without thought and effort. Students were engaged and involved throughout the entire activity, even when their robot failed a challenge. Students were so excited to keep iterating that we kept reducing our end-of-workshop clean-up time to allow for more tests. We were also encouraged by the diversity of solutions that students demonstrated (Figure 6), even when starting with the same two pre-built components. Before the second iteration of our SE activity we were worried that giving students the same components would limit their solutions; however, this does not appear to be the case.

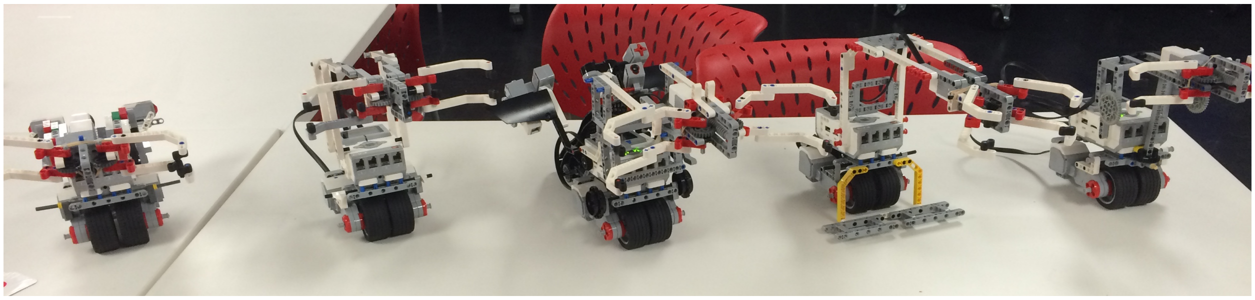

Figure 6: Students demonstrated a large diversity of solutions, even when starting with the same two pre-built components.

Initial Qualitative Assessment of Student Learning

We believe that this activity was successful in helping students to achieve the systems engineering learning objectives set out at the beginning of the paper. During each of the data collection workshops, we facilitated two full-group discussions—one after the first challenge and one at the end of the workshop. We asked questions that aligned with our learning objectives to qualitatively assess students' learning. After the first challenge, we asked students to name some of the factors that they considered when integrating the arm and the chassis. This related to our second learning objective: designers coordinate activities by communicating requirements and interfaces. Students named many of the factors we expected, including:

- *The weight of the arm*, which could cause the whole robot to become unbalanced front-to-back. A group in the second data collection workshop also identified that they initially tried to put the arm on one side of the robot, but it fell over. Therefore, these students thought that *symmetry* of the robot was an important factor.
- *The positioning of the can*, which required that the arm to be a certain height above the table and a certain distance out from the chassis.
- Students in the first workshop noted *a lack of friction* between the claw at the end of the pre-built arm and the can, which caused the can to slip out. Many groups added rubber grips (seen in Figure 4) to provide the required friction. We then added these grips to the pre-built arm in the second workshop.

After students identified these factors, we made the connection to systems engineering by naming these factors as requirements of their robots. While students did not make this connection on their own, they appeared to understand how they had been specifying functional and interface requirements throughout their design—even if they had not been using those terms.

After the second challenge, we asked students, "What are some of the things that you had to consider. What are some of the changes that you had to make?" This discussion was intended to help students think about how the requirements of their robot changed with the second challenge, and how these requirements necessitated changes that propagated through the subsystems and interface. This related to our third learning objective: testing reveals problems and changes propagate to other components. In this discussion students identified how the positioning of the can in the second challenge required them to make the interface taller and the arm further out from the chassis, which in turn required modifications to the chassis so that their robot wouldn't fall over. The students found that this propagation of changes was especially prominent when they attempted to retrieve the heavy soda can, and in the discussion they remarked that it was necessary to add a counterweight to the chassis.

Finally, we ended the workshop by asking students, "How do you think that this activity that we did today relates to systems engineering—the stuff that we talked about at the beginning [of the workshop]." This related to our first learning objective: a system can be decomposed into subsystems. Students responded to our question quickly, identifying how the activity focused on the integration of two separate components that had to function together for the entire robot to be successful:

- "You're getting different parts from different spots and you have to figure out how to put them together."
- "It's like, you have two different pieces and you kinda, like, a way to attach them, like sometimes, like, the calculations get messed up and like, think on the fly how do they work."
- "You have to get the different parts really good and then you can put them together."

We believe that students' comments in these full-group discussions suggest that they were able to productively engage in elements of systems engineering that aligned with our learning objectives. In order to more fully investigate this research question, we are analyzing the video data collected during the workshops to investigate how students used elements of systems engineering while designing, building, and testing their robots.[28] This will help us to have better insight into how all students—not just those who participated in the discussion—were thinking about their robot with respect to systems engineering elements. The primary sources of data are the iPad videos that students produced in order to document their design decisions. This is supplemented with the researcher-collected video data of the whole workshop room, the test setup, and snippets of student groups at different times.

Conclusion

Systems engineering (SE) is a rapidly-growing field, but SE education is often confined to graduate and post-graduate education. We argue fundamental SE concepts are important to introduce to students at an earlier age, even before they enter college. Systems engineering's focus on interdisciplinary collaboration, communication, and the evaluation of design trade-offs provides students with an understanding of how real-world engineers work. Furthermore, understanding how complex systems function and how small changes to one part can affect the entire system are important facets of students' technological literacy.

In this work, we outline three SE learning objectives we believe K-12 students are capable of achieving: 1) A system can be decomposed into subsystems, 2) Designers coordinate activities by communicating requirements and interfaces, and 3) Testing reveals problems and changes propagate to other components. We do not believe this is a comprehensive list, but we hope that it provides a basis for discussion about what SE concepts are important for K-12 students. In this work we also detail our development of an activity designed to convey these SE learning objectives. The final activity and initial qualitative assessment of student learning suggest that students can gain experience with important SE concepts in a single-session workshop. By discussing our entire development process, we hope to warn against potential challenges in developing a SE activity for K-12 students, such as balancing the activity difficulty for each subsystem team and encouraging students to document requirements.

There are many areas of future work for this systems engineering activity. Future workshops could include additional quantitative assessments of student learning through pre- and post-workshop questionnaires. These questionnaires could test students on their recall of systems engineering concepts; ask students to apply systems engineering elements to a hypothetical design problem; or survey the students on their attitudes towards the workshop, systems engineering, and STEM fields in general. Quantitative analyses such as these would support our qualitative assessment of the systems engineering learning objectives. We also plan to develop lesson plans so that others can implement versions of activity. While we have only implemented the workshop with LEGO EV3 robotics and the “toxic waste disposal” challenge, the general framework and systems engineering elements are not only constrained to this platform or challenge. We encourage others to build upon our work to implement similar systems engineering activities with K-12 students. Others could also iterate upon our first workshop, which we ultimately deemed unsuccessful. By reducing the difficulty of the challenge and/or using a simpler building system (such as the LEGO WeDo 2.0 robotics set for 2nd-4th graders), it may be possible to give students a manageable challenge in which they work together in distributed subsystem teams to design, build, and test one robot.

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