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Unplugged Cybersecurity: An approach for bringing computer science into the classroom

Rachel E Fees[1]

Jennifer A da Rosa[2]

Sarah S Durkin[1]

Mark M Murray[1]

Angela L Moran[1]

[1]United States Naval Academy
[2]Johns Hopkins University

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1. Abstract

The United States Naval Academy (USNA) STEM Center for Education and Outreach addresses an urgent Navy and national need for more young people to pursue careers in STEM fields through world-wide outreach to 17,000 students and 900 teachers per year. To achieve this mission, the STEM Center has developed a hands-on and inquiry-based methodology to be used with K-12 educators at professional development workshops and with students through camps, festivals and fairs, and STEM days.

According to recent data, math and computer science (CS) are the fastest growing fields among STEM careers (US Bureau of Labor Statistics, 2016). The Computer Science for All initiative (U.S. Office of the Press Secretary, 2016) urges communities to bring more computer science education into the classroom to meet the rapidly rising need for more CS graduates. As a result, the USNA STEM Center has developed a number of unplugged (without a computer) cybersecurity modules to promote engagement and increase awareness. Topic areas include encryption, networking and social media, viruses and malware, programming, hardware components, authentication and authorization, and hacking.

This article describes the methodology for developing unplugged computer science activities and adapting computer science undergraduate curriculum for K-12 educators and students as an introduction to complex computer science topics.

1.1 Keywords

Cybersecurity, computer science, outreach education, professional development, project-based learning

2. Introduction

According to the U.S. Bureau of Labor Statistics (2016), 51 percent of STEM occupations were in computer science (CS) and mathematical-related fields in 2014, and it is expected that CS and mathematical occupations will increase 13.1 percent between 2014 and 2024. Only eight percent of STEM graduates have degrees in CS (National Science Foundation, 2014). The rise in CS occupations is related to technology advancing very rapidly and a need to meet consumer demands. Therefore, there are more computer science related jobs than there are graduates qualified to fill these positions. The United States Naval Academy (USNA) STEM Center hopes to promote engagement in cybersecurity and bring CS career awareness to K-12 audiences though developing and implementing affordable and engaging CS related activities.

Although use of online tools like social media pages is significant, one study showed that technology users of high school age lack an interest in computer science as a future major or career because they perceive the field as challenging, asocial, and uninteresting (Yardi & Bruckman, 2007). When interviewed by Yardi and Bruckman

(2007), teenagers often regarded computer scientists as those with a solitude career who are "sitting in front of a screen all day" (p. 42) and programming. They also found that many of the female participants strongly perceived computing as a male dominated field with one study participant being the only female enrolled in the her high school's Advanced Placement level CS course (2007). Additionally, some female groups like Latina and African-American women's representation in computer science has declined (National Science Foundation, 2015) and the field does not enroll as my underrepresented racial and ethnic minority groups as other STEM fields such as biology, physics, and math (Lehman, Sax, & Zimmerman, 2017).

In 2011, the Department of Defense (DoD) implemented a strategy for responding to cyber threats to the nation's computer networks and servers. The strategy introduced five initiatives for operating in cyberspace including definitions of cyberspace, how to protect DoD networks and systems, how to partner with other government agencies on cybersecurity, how to develop relationships with allies to strengthen cybersecurity, and how to use rapid technological innovations to the department's advantage (Mudrinich, 2012). In response to the DoD's cybersecurity initiatives, the United States Naval Academy included in its core curriculum that all midshipmen (USNA undergraduates) take two cybersecurity courses regardless of major. As a result, significant resources are available from the curriculum developed for these two courses and other courses required for CS-related majors offered at the academy.

President Obama's Computer Science for All initiative was launched in 2016 as an effort to bring more computer science education (CSE) into public schools. Under the initiative, $4 billion was identified in order to provide professional development and instructional materials to K-12 teachers, and to build effective partnerships (U.S. Office of the Press Secretary, 2016). This initiative came as a response to parents requesting CSE be taught at their children's schools, the lack of Advanced Placement CS (APCS) courses offered throughout high schools, and the shortage of minorities and women in CS courses and careers (U.S. Office of the Press Secretary, 2016). According to Yadav and Korb (2009), just 10% of high schools offer an APCS course and only 2,000 teachers are qualified to teach this course. There is a shortage of CS teachers at the high school level because those with CS backgrounds tend to choose careers in industry over education (Yardi & Bruckman, 2007). Schools are lacking teachers qualified to teach CS, and those who are qualified may be required to follow a curriculum where CS is not highlighted. According to Stephenson (2005), major issues in computer science education are found in school systems which lack administrative support, funding, understanding of computer science as a discipline, and opportunities for teachers to develop technical teaching skills.

The USNA STEM Center works primarily with K-12 teachers via educator workshops believing teachers have sustained influence over student populations. Teachers trained in cyber technology basics can present abstract fundamentals of cybersecurity using hands-on activities to engage students. STEM programs developed to date by USNA provide teachers with significant support including hands-on curriculum exposure, materials and resources to bring back to the classroom, and networking opportunities with USNA scientists and engineers, and also with teachers from other school districts. In the United Kingdom, the Computing at School (CAS) group, a partnership created to improve teaching computer science in UK schools, was successful because teachers were able to work with industry professionals and university academics (Brown, Kölling, Crick, Jones, Humphreys, & Sentance, 2013). Furthermore, Guskey and Yoon (2009) stress that professional development that improves student learning focuses on ideas presented by outside experts who help teachers facilitate content implementation and teachers benefit from participating in professional development that allows them to expand on their content knowledge. As both a military and an education institution, the UNSA STEM Center presents a wide-range of content at professional development workshops by faculty who are active in those STEM fields. Since cybersecurity courses are a requirement for all Naval Academy midshipmen and a number of technical-related majors exist like cyber, computer science, information technology, and computer engineering, there are many faculty equipped to teach computer science and cybersecurity related content to teachers.

Many of the activities developed by the USNA STEM Center are unplugged, or hands-on and experimental activities done without a computer. Unplugged computer science activities are effective because they disassociate a child's thinking of the computer as a tool or toy and replace that with an awareness of the issues that computer scientists face beyond programming (Bell, Alexander, Freeman, & Grimley, 2009). Unplugged activities tend to be less costly and resource-intensive than those which require computer platforms and thus, can reach larger audiences. The USNA STEM Center often works with audiences coming from underserved populations in STEM, and unplugged activities allow all users, regardless of resources, an opportunity to try CS activities. CS Unplugged based out of Canterbury University also stresses the importance of using low-cost materials in addition to having engaging activities that are gender neutral, error resilient, concept-focused, and inquiry-based (Bell et al., 2009). The USNA STEM Center develops activities that include these ideas so that they are accessible for many audiences.

The framework behind unplugged CS activities is constructivist learning theory. Constructivism advances that people learn best by doing, and they actively construct knowledge by interacting with their surroundings, other learners, and facilitators (Kruckeberg 2006; Schunk, 2012). The USNA STEM Center unplugged activities have both a physical and a social component such that knowledge develops through engagement in hands-on activities and social interactions. This aligns with both Piagetian constructivism and Vygotskian constructivism, respectfully (Schunk, 2012). In keeping with constructivist philosophy, the USNA STEM Center workshop instructors take on the role of a facilitator, orchestrating learning experiences and guiding the learner through dynamic dialogue to analyze, construct, and apply CS knowledge.

Research suggests that after engaging in CS outreach, students indicate that they are more interested in CS, have higher cognitive competence, and are more confident in math (Lambert & Guiffre, 2009). The goals of the USNA STEM Center with regards to CS education are to engage teachers and students in complex cybersecurity content areas and promote awareness of cybersecurity as both a field and as a STEM career. The USNA STEM Center develops activities that are broadly matched to general education standards and because the activities are short, affordable, and scalable, they can easily fit into a traditional lesson plan. This article outlines the process to develop and adapt CS activities for implementation into professional development workshops and student events to promote cybersecurity awareness and engagement.

3. Activity Adaptation and Development

The USNA STEM Center has a number of unplugged CS activities that were developed in response to the academy's focus on cybersecurity and each activity is created in a way that follows guidelines established by the USNA STEM Center. While many of the CS activities used by the USNA STEM Center are derived from the academy's undergraduate curriculum, some of the center's activities are adapted and credited from sources outside the Naval Academy such as federal agencies, CS Unplugged, Code.org®, or science museums throughout the world. The activities are adapted so that curriculum is hands-on and inquiry-based as well as low cost and scalable across race, gender, and age. They are also revised to highlight where those topic areas fit into Naval and DoD applications and why the subject matter is important to both civilian and military Navy careers. The STEM Center develops novel activities based on CS concepts that come directly from computer science and computer engineering coursework required for midshipmen due to current emphasis on cybersecurity on the world stage. The computer science and engineering expertise at USNA is a valuable resource for the development of CSE activities by the STEM Center.

While robotics platforms are becoming increasingly popular in school and extracurricular programs, the affordability of these platforms can be a prohibiting factor for many school districts. The USNA STEM Center uses a wide range of robotics and programming platforms, but the STEM Center also encourages the usage of unplugged computer science activities to reinforce CS content knowledge while offsetting cost. These activities can often be implemented with little or no cost, with resources that are easy to obtain, and the materials are more portable than computer hardware – all relevant considerations since many schools involved have limited resources. It is equally valuable in the creation of programs aimed at underserved populations to make the activities scalable regardless of age, race, gender, or income. Additionally, the USNA STEM Center makes all of its activities portable since, as an outreach institution, the activities are often taken to offsite locations. Each activity has a *Navy Notes* section that highlights the activity's STEM content in Naval military and civilian careers and applications. This serves as an opportunity to engage K-12 students in real world applications and show them the relevance of the subject in future majors and careers.

The USNA STEM Center presents both adapted and original CS content to K-12 educators and students in a way that is hands-on and inquiry-based. The activities are sorted into roughly hour-long modules based on topic area such as encryption and decryption (decoding hidden messages), social media and networking, viruses and malware (harmful computer code), authentication and authorization (proving identity online), hardware components, and programming. At every USNA STEM Center professional development workshop and many student interactions, the culminating activity is a longer engineering design module that focuses on solving problems using only household items and by following the engineering design process. Computer science activities have been developed into challenges so that participants can learn about content such as binary counters or logic gates through the engineering design process.

Two examples of CSE activities developed by the USNA STEM Center will be described here. The first, titled *Logic Gates,* is an engineering design challenge created by the USNA STEM Center to fit into the previously defined activity guidelines, but the content was influenced by exhibits featured at the Exploratorium museum in San Francisco. The second, titled *True Colors,* is a shorter activity developed using abstract CS concepts covered in the academy's undergraduate curriculum. The implementation of these and other USNA STEM Center CS activities with both educators and students will also be discussed.

4. Example Activities

The USNA STEM Center currently has about 30 unplugged computer science activities that it uses with its audiences. Two examples are detailed below.

4.1 Logic Gates

4.1.1. Background. Logic gates can both ideally or physically represent Boolean logic and typically require one or more inputs to return a single output (Zambou, Britton, & Harting, 2016). The STEM Center has developed an engineering design module that requires teams to create functioning mechanical logic gates using household supplies such as straws, craft sticks, push pins, bobbins, and more. Prior to developing their designs, participants are shown a mechanical binary counter. Integrated flip-flops used on the binary counter are a favored design aspect for logic gates since they can toggle between different states for an output.

4.1.2. Binary Counter. Many science museums have exhibits that showcase abstract STEM topics, including computer science, in a way that can be understood by any museum visitor. The STEM Center has built cascading mechanical flip-flop counters after being inspired by a demonstration at the Exploratorium in San Francisco. A cascading flip-flop counter allows for a chain reaction between flip-flops, in that the actions of proceeding flip-flops are contingent on what occurred in the previous flip-flops. The flip-flops exist in two states: a 0-representing off and 1-representing on, as in a binary system (Figure 1).

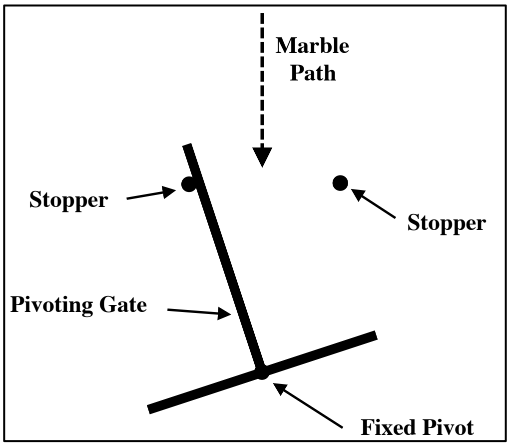


Figure 1. A mechanical flip-flop can switch between states because a pivoting gate moves about a fixed point. To stop the gate from a full rotation, stoppers are added (USNA STEM Center, 2016a).

The flip-flops are made by attaching craft sticks into a T-shape (Figure 2). These shapes are pinned to a foam board using a T-pin, and cocktail straws are glued to the shape to reduce friction against the board. The foam board is elevated on one edge so a marble inserted at the top can travel through the flip-flops easily. The marble is dropped at an entry point while all flip-flops are in the 0-state. As more marbles are inserted, the flip-flops are toggled so that they are either in the 0-state or the 1-state. The states of the flip flops read from left to right indicate the number of marbles inserted in binary.

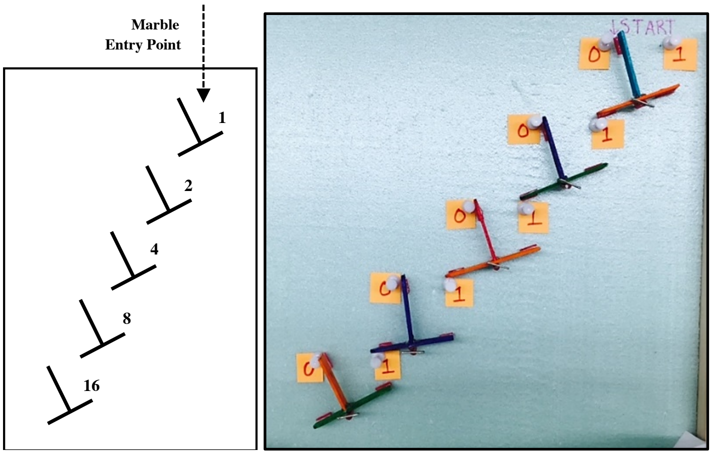
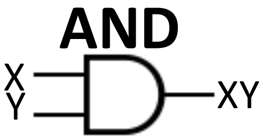


Figure 2. Flip-flops are oriented in a line so that inserted marbles will cause a cascading chain reaction. Each gate represents a binary digit, or bit, shown in the diagram on the left. The numbers on the left image show what the bit would represent in base 10, since each gate represents 2^n where n is the number of marbles. When read from left to right, the number of marbles is represented in binary, seen in the design on the right (USNA STEM Center, 2016a).

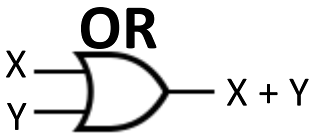
4.1.3. Logic Gate Engineering Design Challenge. Before participants begin the logic gates engineering design activity, they are shown the binary counters. The participants are also given background information about what a logic gate is and Boolean logic.

Participants are grouped into teams of two or three and are tasked to construct a mechanical logic gate that takes two inputs (a zero or one) and gives the correct logic output state for all input combinations. Typical materials provided include foam board, craft sticks, cups, T-pins, hot glue, toothpicks, tacks, and other common household supplies. All designs must meet the following conditions:

1. The participants can choose whether they are creating an AND gate or an OR gate (Figure 3).
2. The base is a 12 inch by 12 inch foam board, similar to the binary counter.
3. Participants must only use the materials and tools provided.
4. The input edge of the base should be elevated between 1 and 4 inches in height.
5. A marble must be started at the "0" or "1" input state for both the X and Y inputs.
6. A single marble should exit at the correct output.
7.



INPUT		OUTPUT
X	Y	X AND Y
0	0	0
1	0	0
0	1	0
1	1	1



INPUT		OUTPUT
X	Y	X OR Y
0	0	0
1	0	1
0	1	1
1	1	1

Figure 3. Teachers are required to either build an AND or an OR logic gate. Outlined for them are input and output charts of each condition to provide them with background information (USNA STEM Center, 2016b).

The designers are required to plan and sketch a design proposal to be approved by a USNA facilitator. Once approved, the designers must construct, test, and iterate their design following the engineering design process and in a given amount of time. When time has ended, all teams watch each design to observe how many solutions (Figure 4) can arise when given the same challenge.

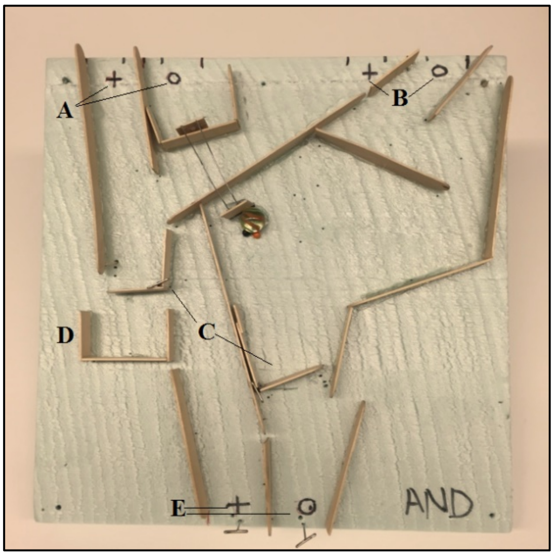


Figure 4. Many solutions can come out of the same challenge. An AND gate is represented where there is an x-input (A) and a y-input (B) denoted with either a "0" or a "+" for 1. Flip-flops (C) are used to change the state as marbles travel down the track. Intentional stops (D) are included so that only one ball is returned as an output (E).

4.2 True Colors

4.2.1. Background. A cryptographic apparatus and method, more commonly known today as the Diffie-Hellman key exchange (DHKE), was filed for patent in 1977 and has revolutionized encryption systems (Diffie, Helman, & Merkle, 1980). The DHKE is an exchange of public keys as a method of enciphering messages (Diffie & Hellman, 1976). The apparatus facilitated the introduction of digital signatures by demonstrating that one-way functions are easily computed in one direction, but nearly impossible to compute in the reverse (Rivest, Shamir, & Adleman, 1978). The method is fairly straightforward in cryptography; however, to a layperson, it may seem overly complex or confusing. The concept of asymmetric cryptography is important to discuss in CSE because it is widely accepted as a reliable encryption method in cybersecurity. The DHKE is taught in required introductory cybersecurity courses at the Naval Academy for this reason.

Rivest, Shamir, and Adleman (1978) familiarize the Diffie-Hellman key exchange by introducing players Alice and Bob, two friends wishing to send a message to one another without an eavesdropper being able to decrypt any of the contents. This analogy has paved the way for an entire array of characters in cryptography developed by Bruce Schneier (1996). To simplify the explanation of the DHKE, Alice and Bob are often regarded as two people with their own private paint colors (or private keys) with access to a public paint color (public key). The two exchange paint in such a way that the final result is Alice creating a paint color that is the same color as Bob's (Figure 5). The exchange was public, so an eavesdropper, often known as Eve, has access to much of the information but what she is missing is the private colors possessed by Alice and Bob. Therefore, Eve cannot arrive at the same color (decrypt the message) since she only heard "garbage" or the ciphertext (Rivest et al., 1978).

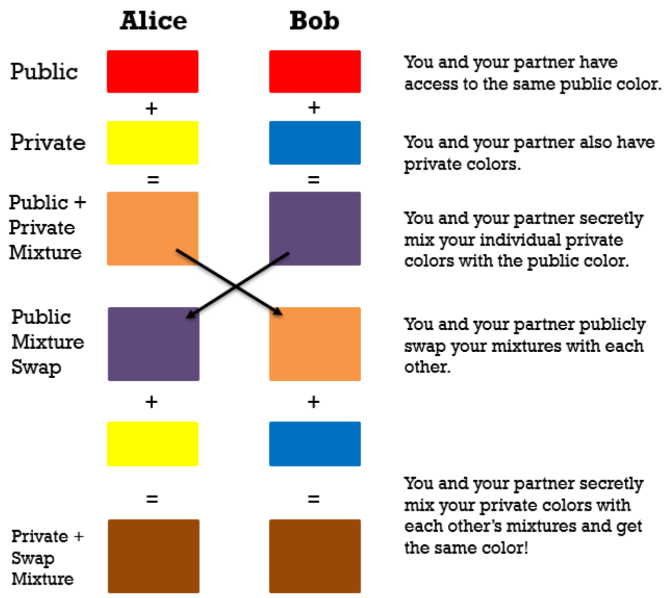


Figure 5. Teachers are given the solution to the Diffie-Hellman Key Exchange after playing the parts of Alice and Bob using diluted food coloring (USNA STEM Center, 2016c).

4.2.2. Activity adaptation. Instead of simply discussing this common analogy, the USNA STEM Center presents the DHKE as a hands-on activity where participants assume the role of Alice and Bob. Each partner is given a cup of diluted food coloring that is private to them; Alice receives yellow and Bob receives blue. The partners also have access to a public colored mixture that is red. They recreate the same exchange above using a specific amount of colors to arrive at the same end color, brown, representing a common secret.

Through iteration, the STEM Center incorporated food coloring rather than paint into the activity because it is easier to mix and clean up during outreach events, fitting into their model of portability. A placemat was created

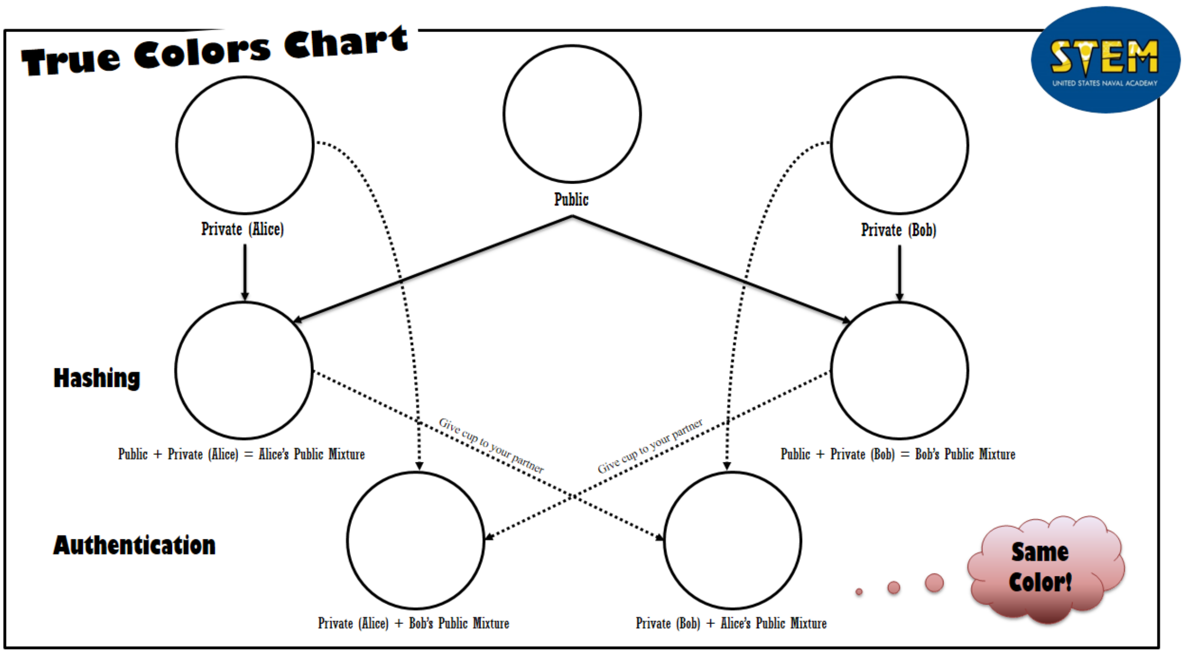


Figure 6. Teachers use a placemat as a guide through the *True Colors* activity (USNA STEM Center, 2016c).

that outlines where the cups should be placed, has arrows to direct the process of adding colors and switching mixtures, and gives instruction on the amount of liquid that needs to be exchanged to simplify the activity (Figure 6). At the end of the activity, the participants have learned an abstract topic area through practice rather than through lecture.

5. Activities in Practice

After the USNA STEM Center develops and adapts activities, the curriculum is used with teachers during professional development workshops or students during camps, festivals and fairs, and STEM days. Instead of rewriting activities to work for specific audiences (elementary, middle, or high school), the activities are designed to be scalable so that they can be presented to different age groups and under different venue circumstances. During the professional development workshops, the teachers work through the activities as if they are students and reflect on how to integrate the content into their classrooms. With students, USNA facilitators predetermine how to present the activity so it is appropriate for the age group and the venue. Two examples of cybersecurity activities in practice by the USNA STEM Center are outlined below.

5.1. Cybersecurity as Professional Development

The USNA STEM Center interacts with over 900 teachers a year through professional development workshops conducted as part of the STEM Center's SET (STEM Educator Training) Sail program. One eight-hour workshop is held onsite each fall and spring semester and two residential week-long programs are held during the summer at the Naval Academy in Annapolis, MD. The STEM Center also travels worldwide to hold remote SET Sail workshops for populations of interest to the Department of Defense. Typically, the one-day events include an introduction session, three hour-long modules in the morning, a working lunch discussion, an introduction to the engineering design process, and a one- to two-hour long engineering design challenge.

The USNA STEM Center held a thematic SET Sail workshop during the fall 2016 session related to computer science, cybersecurity, and robotics. The workshop, titled *Cyber Ops,* was attended by roughly 114 K-12 teachers from 86 public and private schools in the region. Each module was led by a USNA faculty or staff member and facilitated by USNA midshipmen. Teachers participated in three hour-long modules in the morning, attended an interactive lunch session on the topic of truth tables and logic, and in the afternoon, participated in an engineering design challenge building the logic gates previously described. The majority of the modules were unplugged and only one option (of six) required a computer. The sessions offered included encryption and decryption (two sessions), soldering and electronics, viruses and malware, unplugged cybersecurity, and robotics and programming.

The encryption and decryption modules used historic methods to explain modern methods of cryptography. Teachers learned how to use cipher wheels and Scytale rods as well as Morse code, book ciphers, and basic enigma machines to decipher messages. In soldering and electronics, teachers learned how circuits work and soldered their own electronics kit to obtain crucial skillsets used in computer engineering. The viruses and malware module, often used by the USNA STEM Center to address bioterrorism, was adapted as a lesson on the spread of computer viruses. Teachers "infected" one another through interactions made with kitchen chemistry and explored how the spread of disease can be analogized to the spread of malicious infections in computers. In unplugged cybersecurity, teachers learned about authentication, authorization, algorithms, and coding all through unplugged activities. Only one computer-based module was offered on this day where teachers learned about sensors and robotics; however, within that module, half of the activities were unplugged to introduce how robotics platforms communicate and interpret code.

Over lunch, teachers investigated truth tables and Boolean logic with a USNA math department faculty member. They were given different conditions (AND, OR, NOR, XOR, etc.) and statements to determine if the statements were true or false based on those conditions. After learning the terminology, teachers participated in an engineering design challenge where they constructed physical AND or OR logic gates that would output a marble correctly based on input conditions as previously described. The teachers used household materials to create simple machines that would input two marbles and give the appropriate output based on which gate was being represented per the activity addressed earlier.

Throughout the day, the teachers constantly engaged in abstract cybersecurity concepts through inexpensive methods. The teachers were provided supplies and methods to allow for immediate implementation into their classrooms. With sustained access to students, teachers can continue to raise awareness of the relevance of cybersecurity by implementing these activities.

5.2. Cybersecurity and Students

The USNA STEM Center reaches 17,000 students a year via various venues and collaborates regularly with local partners such as Mathematics Engineering Science Achievement (MESA), an academic development program that partners with K-12 and higher education institutions to promote STEM fields (MESA USA, n.d.). The Maryland chapter of MESA is located at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, MD and has a partnership with the USNA STEM Center. On two days each fall since 2011, the USNA STEM Center has brought midshipmen to APL to present hands-on activities to upper elementary students who come from underserved populations in regional Maryland counties. The students rotate between half-hour modules which are facilitated by the midshipmen. Prior to the event, the midshipmen are trained by USNA faculty and staff on the topic area they will teach at the event.

Two MESA days were held at APL in November 2016. The first day was held on November 7, 2016 where roughly 191 students were in attendance from eight public schools and 30 midshipmen facilitated 12 STEM modules. The second day was held on November 18, 2016 and roughly 227 students were in attendance from nine public schools. On this day, 21 midshipmen facilitated 13 modules. The modules ranged in STEM topic areas, and included themes related to cryptology, robotics, and programming. Eighty-two students on the first day and 62 on the second attended the cryptology module. Students learned how to use cipher disks and Morse code in order to decode a message and were introduced to encryption and decryption topics. To address authentication (proving online identity), the students also used Scytale rods which involve wrapping a piece of paper around a rod, writing a message, and unfurling the message so that is unreadable without the proper diameter rod.

Through simple activities, even elementary students can effectively be introduced to the complexities of cybersecurity. The activities were not developed specifically for elementary students, but were scaled so that they could be implemented appropriately with this audience. Even at this young age, the students were exposed to abstract CS concepts and the need to keep systems safe from adversaries which becomes increasingly important as they interact more with the internet and computers later in life.

6. Future Directions

The STEM Center offers two different middle school summer camps. The first camp lasts two weeks and brings students from underserved parts of Baltimore daily to the Naval Academy for STEM enrichment facilitated by the midshipmen. The second is a week-long girls-only day camp for local middle school students and is facilitated by female USNA faculty and staff. Both camps are thematic and the subject changes yearly. While past camps have included some cybersecurity activities, a future camp can be entirely themed with cybersecurity in mind. In a fair or single module setting, it can be challenging to gauge understanding and retention of cybersecurity concepts with the students; however, in a camp environment, the students' progress in learning about cybersecurity can be tracked over the course of the camp. Also, when students explore a single topic area for a longer period of time, they have an opportunity to burrow deeper into the subject matter because the students cover more content than they could in a single day interaction. Additionally, the camps provide mentoring opportunities for both the midshipmen and the USNA faculty members and with a cybersecurity theme, the USNA STEM Center may encourage more cyber and CS majors for future activity development and facilitation. To accomplish these goals, the USNA STEM Center will continue to reach out to the Naval Academy's computer science and computer engineering faculty as well as the unplugged resources that are available through other CS outreach programs and will continue to adapt the activities as technology changes with time.

7. Acknowledgement

The STEM Center would like to acknowledge the Office of Naval Research, the Office of Secretary of Defense, and the Volgenau Chair for Education and Outreach through the Naval Academy Foundation who provide funding to develop and adapt the activities presented here as well as hold the events described.

8. Contributors

Author 1 is a current instructor with the USNA STEM Center, and Author 2 was previously an instructor. Author 3 and Author 4 are the center's associate director and director, respectively. Author 5 is a Mechanical Engineering professor who volunteers his time with the center. All of the authors aided in developing these CS activities and modules.

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