Serious Toys: Teaching the Binary Number System

Yvon Feaster†, Farha Ali‡, Jason O. Hallstrom†
†School of Computing, Clemson University, Clemson SC 29634-0974 USA
‡Department of Mathematics and Computing, Lander University, Greenwood, SC 29649-2099 USA
yfeaste@clemson.edu, falli@lander.edu, jasonoh@cs.clemson.edu

ABSTRACT

The binary number system is the lingua franca of computing, requisite to myriad areas, from hardware architecture and data storage to wireless communication and algorithm design. Given its significance to such a broad range of computing topics, it is not surprising that the binary number system plays a prominent role in K-12 outreach efforts. It is even less surprising that the topic is often viewed as a dreary introduction to the discipline. Motivated by these observations and the potential of binary arithmetic to connect future students to a wide spectrum of computing topics, we have developed a new approach to teaching binary arithmetic in the K-12 curriculum. The approach relies on the use of a “serious toy”, an embedded hardware platform designed to teach the binary number system while engaging visual and kinesthetic learners. We describe the design of the curriculum module and the supporting toy and detail our experiences using the approach in three independent outreach efforts. The results are largely positive, supporting our supposition that teaching the binary number system can achieve strong content understanding and improved attitudes toward the discipline.

Categories and Subject Descriptors
K.3.2 [Computers and Education]: Computer and Information Science Education—CS education, Curriculum

General Terms
Experimentation, Human Factors

Keywords
Binary numbers, computer science outreach, high school curriculum, experimental evaluation

1. INTRODUCTION

To borrow a quotation from the popular ThinkGeek t-shirt, “There are 10 types of people in this world: Those who understand binary and those who don’t.” At the risk of sounding flippant, our work is motivated by the belief that this quotation should be (at least mildly) funny to anyone with even a passing interest in computing.

Binary is one of the first topics introduced in the undergraduate curriculum because it is fundamental to so many subsequent topic areas. Proficiency in binary arithmetic is a requisite skill in the study of computer architecture, data storage, networking, and myriad other content areas. It is no surprise that the binary number system plays a prominent role in outreach efforts aimed at early learners [1,6].

Unfortunately, motivating K-12 students to learn binary is more difficult than motivating these students to learn, say, robotics or computer graphics. A number of experience reports note disproportionately low student engagement and satisfaction when compared to other topics [4,7]. Again, this is not surprising. Our supposition is that this is due to three factors. First, topics like robotics and computer graphics, which have strong visual components, naturally appeal to visual learners (e.g., creating a 3D graph). Similarly, these topics lend themselves to hands-on activities that provide immediate visual and/or tactile feedback, appealing to kinesthetic learners (e.g., playing a video game). Finally, these topics are more “real” for students; they involve physical technology components. Traditional modules for teaching binary arithmetic lack all three, which is unfortunate given the seeming universal agreement that the topic is fundamental, even for early learners.

To support the introduction of binary arithmetic in the K-12 curriculum in a manner that is both informative and engaging, we have developed a new approach to teaching the topic that, as with robotics, simultaneously addresses each of the three identified pedagogical challenges. Our approach relies on a “serious toy”—a small embedded hardware platform designed to teach binary arithmetic at the K-12 level. Students are guided through a series of arithmetic exercises that require the entry of operands, operators, and predicted results via short flashlight pulses that encode binary data. The display consists of an 8x8 LED matrix driven by an inexpensive microcontroller. We have piloted the approach in three independent outreach initiatives with largely positive results. In this paper, we describe the curriculum module, the design of the supporting hardware system, and the results of our evaluation. Our intent is to transform a traditionally dreary exercise format into an activity that engages students and positively impacts their perceptions of the discipline. The results suggest we are on the right track.

2. RELATED WORK

We are not the first outreach team to focus on binary. Sarkar et al. [11,12] describe a variety of kinesthetic ac-

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tivities designed to introduce students to computer organization based on the PIC microcontroller. In one activity, students are taught the basic concepts of bits, bytes, and binary numbers. They are then shown a PIC-based device that demonstrates binary numbers through the use of 8 LEDs. Subsequent lessons cover computer memory, LED matrix manipulation, displays, and speech generation. Each lesson emphasizes the importance of the binary number system in computing. Evaluation results indicate that 70% of the students were satisfied with the hands-on experience and would like more hands-on projects. In addition, 75% of students indicated the PIC project gave them a better understanding of hardware fundamentals, including binary. The activities described in this work differ from ours in that student interaction involved writing a desktop program to turn on the display. Further, their work does not cover arithmetic.

Sakala et al. [10] describe a software tool to teach the binary number system, with a focus on conversion from decimal to binary. The interface prompts the user to enter a number and demonstrates each step of the conversion process using division by 2, with the remainder representing the binary number. To evaluate the interface, a lesson on binary conversion was given to a control group using a traditional lecture method; the experimental group was taught using the interface. The results indicate that the tool-based approach was more effective. The primary difference in this work and ours is this group developed a software tool to teach binary conversion. We developed a hardware tool to teach students binary conversion, in addition to arithmetic.

Goldschmidt et al. [6] describe how several fundamental computer science concepts can be incorporated in the K-12 curriculum, including alternative number systems. They describe how to count in binary using rhythm in physical education. In addition, they explain how the Mayan base-20 system, the Enigma Code, and encryption/decryption can be used as discussion points in a social studies class. As with this group, we use lectures and activities to teach alternative number systems. Our activity consists of a hardware-based tool rather than group games.

Stanley [14] describes his experience using visualization to teach computer science concepts, including encryption/decryption and alternative number systems. As an example, he describes his use of MultiMedia Logic [13] in teaching binary and hexadecimal number systems. Stanley also presents an applet used to demonstrate the relationship between a binary number and its decimal representation using a circuit-based visualization. Again, this work involves learning through software-based visualization, whereas our work depends on hardware-based tools.

Waraich [16] describes a multimedia learning environment, used for lessons focused primarily on computer architecture, including binary arithmetic and logic gates. The target audience includes 1st year computer science undergraduates. Students using the instructional environment received higher test scores than those who did not. As with the previous work, this work uses software to teach binary and logic gates.

Chun et al. [1] describe a web-based system designed to help teach K-12 students and educators basic programming skills. An LED kit used to display binary numbers and images is used with the web application. The example discussed in their paper is based on lighting the LEDs to represent decimal numbers using a single row. This work incorporates both software and hardware to demonstrate binary conversion. However, with only a single row of LEDs, they cannot teach binary arithmetic.

CS Unplugged [3] uses games to teach computer science concepts, including binary numbers. The binary games focus on counting with binary and relating the importance of binary to computer science. Our module also discusses the importance of binary in computing, along with converting binary numbers and performing binary arithmetic.

3. WHY FOCUS ON BINARY?

According to the National Council of Teachers of Mathematics [9], number systems should be introduced to students as early as kindergarten. Similarly, new K-12 curriculum recommendations published by the Computer Science Teachers Association [15] include the binary number system. This includes the introduction of binary to K-3 students through a demonstration of data representation using 0s and 1s (page 13). Their report states that by completion of grade 9, students should be familiar with binary numbers and logic circuits (page 16). Their report also indicates that by the end of the 10th grade, students should know the relationship between binary and hexadecimal (page 18).

To gauge computing educators’ perceived need for teaching binary to potential computing students, we developed a brief survey and sent it to 30 computing educators at a range of institutions (6) external to our own. The survey is shown in Listing 1. Participants were asked to rate their level of agreement with each of the 5 statements, choosing from strongly disagree, moderately disagree, disagree, agree, moderately agree, and strongly agree. We received 10 responses. While the sample size is too small to draw definitive conclusions, the results are informative, even anecdotally: Table 1 shows that the results were, overall, positive regarding the need for computing students to understand binary. One interesting observation is that while 30% of respondents indicated that binary is relatively unimportant in the courses they teach (statement 4), all respondents agreed that understanding number systems other than base-10 is important for computing students (statement 1).

4. APPROACH

Our approach to teaching the binary number system consists of a 75-minute lecture, followed by a review and active
learning activities based on the embedded toy. The lecture occurs during one class period; the latter components occur during a subsequent period (on another day).

### 4.1 Lecture

We begin the lecture by reviewing base-10, motivating how and why we group by 10s. This is done by holding up two closed fists and asking students to count how many fingers are held up. When they respond with zero, we write the digit 0 on the board. Next, one finger is held up, and the exercise continues until we get to 10 fingers. We note that nine objects can be represented by a single digit, but another column is needed if we have ten or more objects. Similarly, if we have ten groups of ten objects each, a third column must be added. We conclude by noting one explanation for why we count by 10s: Humans typically have 10 fingers!

Next we introduce the binary number system. To continue the finger counting example, we ask students how many digits we might use, and how high we might be capable of counting if we were aliens with only two fingers, similar to [5]. While it may sound silly, the exercise motivates the concept well. As with base-10, we discuss the grouping principle and note when a new column must be added. Using an example similar to that shown in Figure 1, we illustrate how elements can be grouped by twos, as well as tens. As an exercise, we give the students several small numbers and ask them, using grouping, to write each number in decimal and binary.

This exercise was designed to help students understand that 10 is effectively an arbitrary choice; any other base could be used. Next we discuss how tedious this translation approach would be for large numbers, and then introduce a decimal-to-binary conversion approach based on repeated division by 2. When demonstrating this method, we explain how the quotient represents the number of groups that could be formed, and the remainder represents the remaining elements. We next demonstrate the reverse approach, converting a binary number to a decimal number. We start the discussion by noting the value of each digit in a decimal number. We explain that the value is the product of the digit and a power of 10; the power value depends on the digit’s position. We then adapt this idea to binary numbers. When students are comfortable with the conversion process, we introduce binary addition and subtraction.

We conclude with a discussion of why binary numbers are important in computer science, noting that the language used by computers is limited to 1s and 0s. We use the analogy of a light switch and explain that combinations of these switches allow the computer to operate using large numbers.

### 4.2 Binary Toy

We begin the second class period with a review, and then introduce the embedded toy, noting that the toy works on the same principle as a computer, i.e., it receives input, processes the input, and displays the results. The students are then divided into smaller groups, and the toy is demonstrated in each group. Students are assigned several binary conversion, addition, and subtraction problems, and are instructed to perform the operations on paper before validating their work using the toy.

#### Architecture

The embedded platform consists of an input device, two processors, and an output device. The input device is a photoresistor wired to a microcontroller (and triggered by a flashlight). When the beam of the flashlight is directed toward the photoresistor, a change in resistance is detected and read by an AT-Mega168 microcontroller. The duration of the resistance change is recorded and compared with a specified threshold. If the duration exceeds the threshold, a 1 is recorded; otherwise, a 0 is recorded. Using serial communication, the AT-Mega168 transmits the data to an AT-Mega8515 microcontroller. The AT-Mega8515 is responsible for receiving the data and driving the output device, an 8x8 LED display.

Six of the eight rows on the LED display are used, as shown in Figure 2. The first two rows are used to represent operands. The third is used to display the predicted addition or subtraction result. The fourth represents the correct answer to the problem. The sixth is used to display the operation being performed. Finally, the eighth row displays the last bit position entered.

#### Toy Operation

To begin using the toy, students must direct the flashlight beam on the photoresistor for a count of ten. The display driver then turns on the first row of red LEDs to indicate that it is ready to receive the first operand. The operands must be entered from most significant bit to least significant bit. To enter a 1, the flashlight is focused on the photoresistor for three seconds. A 0 is captured by a shorter beam. The output display denotes a 1 by displaying a red LED; an unlit LED denotes a 0. To assist students in keeping track of the bits entered, the eighth row displays a red LED for each bit entered. After all eight bits are entered, the student must verify her entry. If satisfied, a 1 is entered; otherwise, the board will clear the row and allow the student to re-enter the number. This process is repeated for the second operand. After accepting the second operand, the red lights on the sixth row turn on, indicating the need to enter the operator. Two bits must be entered: ‘11’ for addition, ‘10’ for subtraction. The student must also confirm her choice of operation. At this point, the third row of LEDs is lit, indicating the toy is ready to receive the predicted answer. The students enter the predicted result beginning from the least significant bit. Upon confirmation, the fourth row displays the correct answer, in green lights, for the student to compare with her’s.
5. PILOT GROUPS

We piloted this approach with three groups of high school students. Two of the groups were participants in a university summer program. The third group consisted of students from a nearby high school.

5.1 Emerging Scholars

The Emerging Scholars program was established in 2002 with a mission to reach out to high schools located in areas which, according to the US Census Bureau, have a high poverty rating [2, 8]. Student participants are chosen because they exhibit the potential to succeed in higher education, but lack the economic and social support needed to make attending college a reality. Participants in this program are provided summer experiences for three consecutive summers. During the summers, the students are taught the importance of basic skills such as reading, writing, math, and science. During the students’ third summer in the program, they follow a class schedule that mimics that of a freshman. This affords students the opportunity to experience, in a small way, what it is like to be a college student.

For our pilot project, we engaged two groups of Emerging Scholars, seniors and juniors. Each group was divided into two sections. Each senior section, referred to as ES Senior 1 and ES Senior 2 in our evaluation, had 12 students participate. The junior sections, referred to as ES Junior 1 and ES Junior 2, had participants totaling 15 and 17, respectively.

5.2 Local High School

The participating high school students were chosen from a mathematics course, Statistical Analysis, classified as College Preparatory (CP). The class was chosen because the students’ expected abilities appeared similar to those of the Emerging Scholars groups. As with the Emerging Scholars groups, these students had no predetermined interest in computer science. There were 34 participants, 6 juniors and 28 seniors. This group will be referred to as HS.

6. PILOT STRUCTURE

To evaluate the role of the toy in improving students’ knowledge of binary numbers, we taught the pilot groups using different approaches.

Lecture Only. We met with the ES Senior 1 and 2 groups for only one day. They were taught the binary number system using lectures only. This group was not introduced to the binary toy. Pre- and post-surveys were administered.

Lecture and Prototype Toy. We met with the ES Junior 1 and 2 for two days. On the first day, we presented the lecture on the binary number system using the same material and style as the first groups. Pre-surveys were administered before this class. On the second day, we reviewed the lecture material and demonstrated a prototype of the binary toy. We also discussed the development process used to construct the toy. The prototype was developed using a breadboard setup, as shown in Figure 3a. Only two prototypes were available, so we divided the students into two smaller groups (7-8 per group) and let them take turns practicing addition and subtraction using the prototype. At the end of this meeting, students were given the post-survey.

Lecture and Assembled Toy. We met with the HS group for two days. The format of the first day was identical to the previous offerings. Since this group was twice the size of the ES Seniors and ES Juniors, we divided the students into two groups of 17. One group was introduced to the fully assembled version of the binary toy shown in Figure 3b. They were asked to practice converting, adding, and subtracting binary numbers using the toy. While the first set of students were playing with the binary toy, the second set of students were learning about the toy’s development process. Students were given the opportunity to examine the breadboarded model of the toy and learn how the complete prototype was constructed. To allow students ample time to use the toy, the groups swapped learning areas after approximately 25 minutes. At the end of the period, a post-survey was administered.

7. EVALUATION

The pre and post-surveys consisted of 15 Likert-style statements, shown in Listing 2. The students were instructed to rate their level of agreement with each statement, as in the educator survey: strongly disagree, 1—strongly agree, 6.

7.1 Emerging Scholars

Statements 12-15 were not included in the statistical significance analysis because these statements could not be answered until after the presentation of the material. For the remaining 11 statements, a two sample F-test for variance was performed. Once the variance was determined, the appropriate two sample t-test was performed to determine if the pre/post difference was statistically significant (5% p-level). Of the 44 statistical analyses performed, 31 (70%) indicated a significant change in the mean response. We categorized the statements into three groups: Of the 15 total statements, 2 were related to student interest (statements 1-2), 9 to student understanding (statements 3-11), and 4 to students’ perception of the program (statements 12-15).

Interest in Computer Science. These statements were designed to measure the impact of the program on student interest in computer science. Although the change in mean for 7 of the 8 responses was not statistically significant (statement 1, ES Senior 2, significant decrease), we do
I think I could write the number 200 using only 0’s and 1’s.

Computer science seems like it would be fun.

I might be interested in majoring in Computer Science in college.

I think I understand why 00000010 subtracted from 00000101 = 3.

I think I understand why 00000101 added to 00000010 = 7.

I think I understand why 00000010 subtracted from 00000101 = 3.

I would like to participate in additional computer science outreach programs. This was not surprising since the ES Junior 2 group showed the highest interest in majoring in computer science. Lastly, three of the four ES groups indicated they enjoyed learning about binary. It is interesting to note that the ES Junior 1 and 2 groups averaged a score of 5.1 for this statement, whereas the ES Senior 1 and 2 groups scored 3.5 and 4.3, respectively. This suggests the binary toy had a positive impact.

**Content Understanding.** These statements were designed to measure student understanding of the material presented, in particular the impact of the toy. The statistical analysis showed that 30 of the 36 t-test analyses represent a significant change between the pre- and post-surveys. It is also notable that all of the results for this category indicate an increase in (perceived) content understanding. We focus on statements 9 - 11, which relate to student understanding of converting, adding, and subtracting binary numbers. Knowledge of each of these concepts is reinforced through the use of the binary toy. In each case, the analysis indicates a statistically significant increase between the pre- and post-surveys. In addition, the ES Junior 1 and 2 groups show a higher post-score on each of these three statements than the ES Senior 1 and 2 groups, as shown in 5a, 5b, and 5c. Since the ES Senior 1 and 2 groups were not introduced to the toy, we believe this suggests the binary toy had a positive impact on student understanding.

**Structure of Outreach.** These statements were designed to gauge whether students enjoyed the format of the program. Pre-survey data was not considered since students were unable to rate these statements until after the program was completed. As shown in Figure 4c, both ES groups, on average, agreed or moderately agreed that the instructors did an appropriate job. Also, on average, both ES groups enjoyed the format of the outreach module. However, the ES Junior 2 group was the only group that indicated they would like to participate in additional computer science outreach programs. This was not surprising since the ES Junior 2 group showed the highest interest in majoring in computer science. Lastly, three of the four ES groups indicated they enjoyed learning about binary. It is interesting to note that the ES Junior 1 and 2 groups averaged a score of 5.1 for this statement, whereas the ES Senior 1 and 2 groups scored 3.5 and 4.3, respectively. This suggests the binary toy had a positive impact.

1. Computer science seems like it would be fun.
2. I might be interested in majoring in computer science in college.
3. I think I understand the need for alternate numbering systems.
4. I think I understand why humans use the decimal number system.
5. I think I understand the value of binary numbers in computer science.
6. I think I understand the concept of a binary numbering system.
7. I think I understand the relationship between decimal and binary numbers.
8. I think I understand the concept of a binary numbering system.
9. I think I could write the number 200 using only 0s and 1s.
10. I think I understand why 00000101 added to 00000010 = 7.
11. I think I understand why 00000010 subtracted from 00000101 = 3.
12. I think the teacher did an appropriate job explaining the material.
13. I like the format of this outreach program.
14. I would like to attend more outreach programs related to computer science.
15. I like learning about binary numbers.

*Listing 2: Survey Statements*
7.2 High School Classroom

Pre-treatment survey data was unavailable for this pilot group. Hence, our analysis is based only on the post-treatment survey. As before, in the evaluation of the final pilot we group the survey statements into three categories, measuring interest, content understanding, and module organization. For each statement group, we compute the average and standard deviation across the response data for all of the constituent statements. The results are summarized in Table 2 below:

<table>
<thead>
<tr>
<th>Statement Category</th>
<th>Average</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest in CS (S1-2)</td>
<td>2.40</td>
<td>1.28</td>
</tr>
<tr>
<td>Content Understanding (S3-11)</td>
<td>3.71</td>
<td>1.06</td>
</tr>
<tr>
<td>Module Organization (S12-13)</td>
<td>3.29</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Recall that a score of 3 denotes moderate disagreement, and a score of 4 denotes moderate agreement. Accordingly, the average scores in the content understanding category indicate that students completed the program with a generally positive impression of their content understanding. Unfortunately, they had a less positive view of the module’s organization and their likelihood of pursuing a computer science degree. It is interesting to note that the high standard deviation values indicate significant variation in the response data. Indeed, an analysis of the individual statements reveals that approximately half resulted in bimodal response distributions, with frequency peaks on either side of 3. This suggests that the class was partitioned in two — those who “got it”, and those who didn’t.

We posit several potential explanations for the overwhelming response data. First, with regard to interest, this was the only pilot group that was not self-selected to participate in an outreach module. They elected to participate in a statistical analysis course, and were then required to participate in the binary arithmetic module. Their pre-existing interest in the displaced statistical analysis content may have biased their attitudes toward the outreach content. With regard to module organization, these results are not surprising. The classroom setup made it difficult to power all of the toys in a manner that supported small group participation. The devices were arranged on a central table, and students took turns participating in a large group. Our impression is that only half of the students interacted with the toys, which aligns with the bimodal response data noted above.

Finally, it is impossible to tell whether these figures represent improvements over students’ baseline impressions given the absence of pre-treatment data.

8. CONCLUSION

We began with the observation that the binary number system is central to a host of areas across computing. It is widely regarded as a fundamental topic, featured in a number of popular outreach programs. Unfortunately, there is evidence that existing approaches to teaching this topic inadequately engage and excite students. In response, we described a new approach to introducing binary arithmetic in the K-12 curriculum using a supporting embedded platform that simultaneously engages visual and kinesthetic learners. The evaluation results are largely positive across the three pilot studies that have been conducted. Our hope is that this approach will serve as a model for introducing a fundamental topic that is often perceived as dull by young learners.

We are currently developing several software extensions to improve the toy’s interface. As an example, upon completion of each task, the student will receive immediate feedback in the form of a scrolling message. Further, we are developing extensions to broaden the content coverage provided, including binary multiplication, division, and, logical operations. We are also scheduling pilots with middle and high school students to evaluate the effectiveness of the extensions.

We conclude by noting that the embedded platform presented in this paper is the first in a suite of “serious toys” that we are developing to support computer science education. These toys, when designed and used appropriately, have the potential to reenergize the pedagogical landscape around fundamental topics that are often difficult to teach in a manner that is both informative and fun.

9. REFERENCES

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