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RET: Integrating Hands-on Experiments and Simulators for High School Computer Science Probability and Programming Education

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Introduction

In introductory computer science, students struggle to translate real-world probability events (e.g., flipping a coin) into abstract logic using random number generators (RNGs) and selection structures. For example, while flipping a coin is intuitive to understand the result will be heads o or tails, students often fail to map it to a code statement like RANDOM (1, 2). The confusion grows when dealing with more complex probabilities such as with a spinner with different colors. Existing pedagogical strategies use physical manipulatives or digital simulations in isolation to teach these concepts. This paper presents a cohesive scaffolding progression developed under a National Science Foundation Research Experience for Teachers (RET) program.

The objective of this work was to 1) identify concepts to be learned using hands-on experiments, simulator, and gaming, 2) adopt or create hands-on experiments, simulations, and games to stimulate learning, and 3) create an integrated lesson plan. To bridge the gap between concrete probability and abstract programming, we implemented a three-stage approach: 1) physical simulations to understand ground truth data, 2) computer simulators to visualize larger datasets, and 3) gamified assessment and implementation using the Micro: bit platform. We performed an evaluation of the curriculum that included pre- and post-tests and opinion surveys to measure gains in conceptual mastery.

Batanero et al. mentions that chance in nature is important to understand and function in everyday society [1]. The topic of probability is included in many countries. However, it does not mean that it will be taught well and learned in a correct manner. Probability is mainly used to model situations in the real world. Young learners have an intuitive understanding of probability and use words such as "probably" and "unlikely". Teachers can use this fact to make their understanding more concrete. Games are helpful to use when thinking about probability.

Akpinar and Aslan review the history of using computing tools in learning starting from LOGO and going to more modern tools such as Scratch [2]. Scratch is an example of a creative computing tool and its use can help with mathematics education too. Students had a better feeling towards mathematics after using Scratch and it helped them to reflect on their learning. The research had students make video games in Scratch and how it helped with their understanding of probability. Students were assessed with a pre-test and a post-test consisting of 32 multiple-choice questions. The students showed growth in knowledge in probability.

Kuhn et al. use a computational modeling and simulation approach for teaching probability [3]. Teachers were included in the process. In addition to simpler examples, a software tool was created to help. The students could better understand how the software could generate random numbers and helped with their knowledge of probability. The authors state that modeling is an important step in the learning process. Modeling is used to construct some part of the real world.

Games such as video games help students learn because players are motivated to improve [4]. Games can immerse the students and be more engaging than formal education. Games help with some of the following learning principles: interaction, production, risk taking, and conformance before competence [5]. Playing a game provides feedback that can facilitate learning. The term "serious games" is sometimes used to describe games that can help students to develop real-life problem-solving skills. Hsieh [6] presents three games to help students learn about automated system design. A quiz game patterned after "Who Wants to Be a Millionaire" allows students to answer questions about hardware devices such as sensors and relays. A wiring game allows students to practice interfacing devices with controllers. Finally, an automated system design game allows students to design a layout for a cellphone assembly line. Gamification is also increasing through the use of smartphones [7]. Evaluation results suggest that game use positively impacts student motivation and learning. Some popular game development tools used for education include Kahoot, GimKit, Quizlet and Quizizz. These tools make it easy for students to participate and allow tracking progress, viewing quiz results, levels, feedback, badges and a leaderboard.

Simulation helps with cognitive skills such as acquiring knowledge [6]. Some studies show improvement in learning. Simulations allow the students to try different inputs and observe the output. Some research has also shown that students show better results than with traditional lectures. Students also have reported a positive experience and that simulations help with their decision making, awareness and learning retention.

Methodology

For this work, three different types of tools were developed to facilitate students' learning about probability: (1) physical simulations, (2) computer simulators, and (3) learning assessment games.

The physical coin simulation is designed to illustrate the concept of probability through the act of flipping a coin. The primary purpose is to demonstrate the basic concept of probability with a binary outcome (heads or tails). In this activity, students flip a coin and observe the outcome. The students predict and record the outcomes (heads or tails) of multiple flips. They discuss their results and use the collected data to discuss concepts such as the theoretical probability (50% for each outcome) versus experimental probability (the actual outcomes observed). After completion, the students will understand that the experimental probability will become closer to the theoretical probability as the number of samples increases.

One computer simulator is a coin flip simulator (Figure 1) [8]. The tool keeps track of the experimental results for the students such as the number of heads/tails, the percentage of heads/tails and the total number of coin flips. This tool helps reinforce the understanding of the physical simulation of flipping a coin. It helps to make the concept of experimental probability more concrete and shows that results may differ from theoretical probability but that the experimental probability approaches the theoretical probability as we increase the number of trials.

Figure 1. Coin flip simulation reinforces the concept of experimental probability

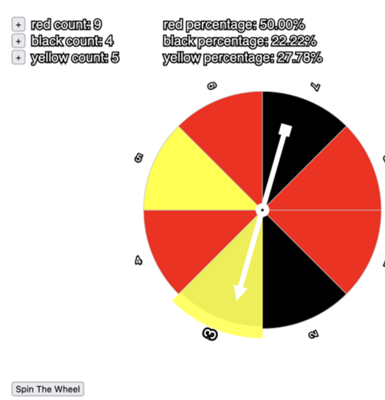


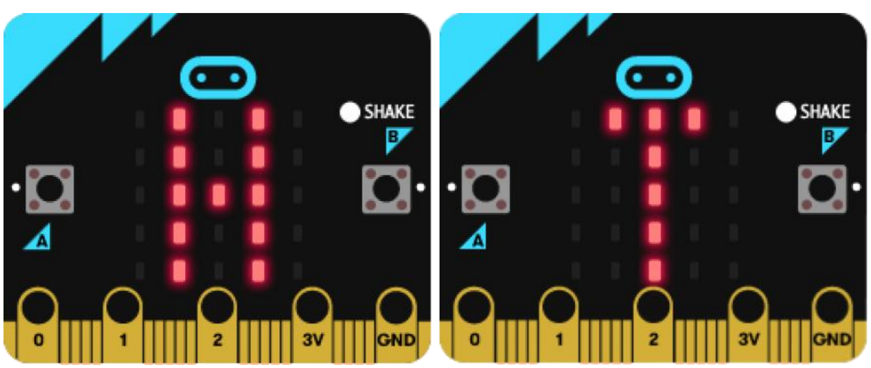
Figure 2. Color spinner simulator

In addition, a color spinner simulation (Figure 2) was created to simulate outcomes based on a spinner with different colored sections. This simulation is used to help students understand probability in scenarios with multiple outcomes, each with different probabilities. First, we introduce the spinner and explain the colors and their respective probabilities. Next, the students simulate spins and observe the distribution of outcomes. The students analyze their data and compare theoretical probabilities with experimental results. For this simulation, the theoretical probabilities are 50% to land in red, 25% to land in black and 25% to land in yellow. The students learn that the colors do not have to be connected and that the probabilities would be the same if they were. This will be extended when the students create their own simulation.

Finally, Micro Bit, a pocket-sized programmable computer, was used to allow students to program their own coin flip simulation. Students can program the Micro Bit in Microsoft MakeCode using a learner-friendly block-based language. Students who are more comfortable with programming have the option to use JavaScript or Python. They use concepts that were covered earlier—variables, random number generation, sequencing and selection—to complete their program. An online Micro Bit simulator is also available for use in classrooms without physical Micro Bits. The student can test their program with the online simulator. The students program the Micro Bit to show heads (H) or tails (T) when it is shaken (Figure 3). Each shake is considered as the action of flipping a coin. After successfully creating the program, it is downloaded to the Micro Bit. The Micro Bit acts as a physical simulator. It provides immediate visual feedback and the physical aspect of shaking the Micro Bit enhances understanding. The active engagement with technology improves student results. The students learn that they can generate any two random numbers where one of the generated numbers represents heads and the other represents tails. This can be extended to a larger set of random numbers with even cardinality where half the numbers can represent heads and the other half represents tails.

Students work on a second, more challenging program to create a simulator for a color spinner. They brainstorm a way to create a program that replicates the spinner from the online simulation in Figure 2. The program builds on the concepts in their coin flip program. We use the Micro Bit to show different colors in text with their corresponding percentages. Shaking the Micro Bit acts as a spin this time. The color spinner has disjointed color segments. The simulation can be programmed with random numbers between 1 and 8, inclusive. Various ways to accomplish the simulation are illustrated in the pseudocode in Table 1.

Students may need assistance to explain why the various solutions are equivalent. The students learn that a two-way conditional statement is not sufficient. A nested conditional statement is required for this simulation.



(a) (b)

Figure 3. Micro Bit Simulator. When Micro Bit is shaken, it displays (a) heads or (b) tails.

Table 1. Pseudocode illustrating methods for creating a spinner simulation in Micro Bit.

Method 1	Method 2	Method 3

r <- Random(1, 8)
if r <= 4 then
   Display("red")
else if r <= 6
   Display("yellow")
else
   Display("black")
end if
	r <- Random(1, 8)
	if r = 1 or r = 4 or r = 6 or r = 8 then
	   Display("red")
	else if r =3 or r = 5
	   Display("yellow")
	else if r = 2 or r = 7
	   Display("black")
	end if
		r <- Random(1, 100)
		if r >= 1 and r <= 50 then
		   Display("red")
		else if r >= 51 and r <= 75
		   Display("yellow")
		else
		   Display("black")
		end if

The learning assessment game is designed as an interactive tool to assess and reinforce understanding of probability concepts in computer science. We use GimKit to assess students' understanding in a fun manner. Students can see how they perform and there is a leaderboard and short game breaks during the assessment. The tool provides immediate feedback to improve learning. The students are engaged and motivated when using this tool. We use the game results to assess understanding and identify areas for further instruction.

Each of these tools, physical simulations, computer simulators, and learning assessment games, provides unique ways to engage students in learning probability. They help with different learning styles and preferences, from hands-on exploration with physical simulations to interactive digital experiences with computer simulators. Students are also engaged with gameplay in the learning assessment games. Together, they form an approach that improves understanding and application of probability concepts for computer science.

Evaluation

The objective of the evaluation is to see how much the students learned about the concepts, if they can apply the concepts and if they like the tools (opinion survey). Three instruments were developed—a pre-test, a post-test and an opinion survey (Table 2).

Table 2. Tools used and concepts evaluated by each evaluation instrument.

Evaluation Instrument	Tool Used	Concepts covered
Pre-test	GimKit - multiple choice gamified assessment	Probability, random number generators, selection statements, simulation, understanding program code
Post-test	GimKit - multiple choice gamified assessment	Probability, random number generators, selection statements, simulation, understanding program code
Opinion survey	Google Form - short answer	Gauge opinions about the lesson, what students liked and how it can be improved

The first evaluation instrument is the multistage pretest. The pretest is administered before any formal instruction on the lesson begins. The primary objective is to assess the students' initial understanding of fundamental probability concepts for computer science. We then test again after the lecture and once more after the student activity. In this way, we can gauge how much they learn after each part. The pretest consists of multiple-choice questions designed to cover the key concepts and definitions. In the pretest, each student plays individually and students can see the top leaders in the game. GimKit was used to deliver the pretest.

The post-test is administered after students have received the initial lecture instruction on the concepts. The students have also had discussions and have completed the interactive activities. The post-test assesses the extent to which students have learned and retained the material covered during the course. It includes multiple-choice questions

An opinion survey is designed to gather feedback from students regarding their experience with the instructional methods used, their perception of their own learning, and their attitudes toward the topic of probability in computer science. It includes questions that assess students' satisfaction with different aspects of the lesson, such as clarity of explanations, usefulness of activities, and overall enjoyment of the learning process. Examples of questions include

Please rate on a scale of 1-5 the following statements based on your experience in this course:
1. The lectures helped me understand probability concepts used in computer science.
2. I found the hands-on activities valuable for learning.

The opinion survey was made available after the lesson was finished.

Scores from the pre-tests and the post-test for each student were used to provide quantitative measures of their initial, intermediate and final understanding of the concepts. A quantitative analysis was performed on pre- and post-test scores for 28 students. A paired two-sample t-test for means showed a statistically significant improvement in student performance ($t(27) = 4.92$, $p < 0.001$). The mean score increased from 82.6% (variance = 0.021) on the pre-test to 96.0% (variance = 0.006) on the post-test. This represents a learning gain of approximately 13.4%. The variance decreased significantly and indicates a higher consistency in student understanding. An We use feedback from the opinion survey to understand students' attitudes and opinions toward the course and instructional methods used in order to improve. Results showed a 12% improvement in post-test scores showing an improvement in learning. Furthermore, approximately 74% of students agreed or strongly agreed that the lesson improved their understanding of probability.

Conclusion

We described an approach for teaching probability concepts related to programming that uses physical simulations, computer simulators, and learning assessment games. This approach was implemented and evaluated in an introductory high school computer science course. Students showed meaningful improvement in their understanding of probability concepts.

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