Steerable Environmental Simulations for Exploratory Learning

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Abstract: This paper presents the software design for three interactive simulations on the subject of Earth and Environmental science in grades 5, 6 and 7. These simulations together with some programming activities have been successfully integrated into a series of instructional modules for local New Jersey elementary and middle schools. The goal of these modules was for the students to explore the steerable parameters of the simulations and develop their computational and mathematical thinking. In this paper, we present three simulations we developed, discuss their design and examine student assessment results that were collected and analyzed using statistical inferences. Our findings illustrate the effectiveness of such enticing exploratory learning processes for developing students' reasoning of Earth and Environmental science, computational thinking and mathematics.

Introduction

Earth and Environmental Science (EES) studies the earth's dynamic history and aims to address the emerged environmental challenges because of human activities. It offers a rich context for investigating STEM education as it is a multidisciplinary field integrating almost every discipline of science, such as physics, biology, chemistry, geology, ecology, mineralogy, and oceanology. The United States spends approximately $1.5 billion each year on environmental studies research, however these efforts are successful only if their results are widespread and implemented among communities (Bostrom, Morgan, Fischhoff, & Read, 1994). An example of such efforts are the eight grand challenges in Environmental Science identified by the National Research Council (NRC, 2000), which indicated human activity as the primary reason behind this environmental imbalance. Consequently, it is critical that we, as citizens, acknowledge our responsibilities for using the environment and work in unison with nature.

We need to educate our next generation of citizens on the importance of exploiting the natural environment in a sustainable way and studying its profound impacts on global society (Bostrom et al., 1994). For instance, students should be able to consider "environmental effects" even when making basic choices between paper or polystyrene cups, plastic bags and bags made from environmentally friendly materials (Bostrom et al., 1994). These experiences help them in later years to have the ability to judge different bills and policies passed by the government (Bybee, 1993; Shepardson, Niyogi, Choi, & Charusombat, 2009). Earth and environmental topics, such as global warming, pollution and traffic not only provide a "natural context for studying science through personal and social applications" (Shepardson et al., 2009, p. 2), but also have the potential to help our students understand and design policies that consider the wellbeing of their community.

This paper describes our efforts aiming to nurture the next generation of innovators by advancing student learning through a seamless integration of earth and environmental science, mathematics and computer science to (1) design and implement instructional modules that integrate computational and mathematical thinking into earth and environmental science education in Grades 5, 6 and 7, and (2) study and refine the instructional modules with Grade 5-7 students to monitor effects on student learning. The instructional modules utilize Scratch and Netlogo simulations and are created for teachers to integrate into their science, math and technology classrooms. Some key elements of computational thinking, namely problem decomposition, abstraction, algorithm thinking and generalization are being interleaved into the activities at a pace that is appropriate for students' grade according to Stephenson and Valerie (2011). The order of cognitive skills in terms of learning, applying, analyzing, evaluating and creation known as the Bloom's Taxonomy are considered in our project planning (Anderson and Krathwohl, 2001). The instructional modules are taught by teachers from various New Jersey public school districts.

In this paper, we describe some of the simulations we designed on Netlogo and discuss our design decisions. More specifically, we explore:

a) What type of simulations can be designed that assimilate computational and mathematical thinking into Earth and Environmental Science?
b) How effective are the instructional modules that integrate these simulations for improving the students' learning of Earth and Environmental Science, mathematics and computational thinking?

Methods

We used a design-based approach (Brown, 1992; Cobb, Confrey, DiSessa, Lehrer & Schauble, 2003) to design, implement and refine the simulations and the instructional modules and study students' thinking as they interacted with those modules. To assess students' learning of concepts and practices pre- and post-intervention assessments with treatment and comparison groups were used aiming to permit the contrast and comparison of the cognitive results for participating and nonparticipating students (Cobb & Gravemeijer, 2008). The comparison group was chosen from the same school as the treatment group, so that the demographics of students are the same for both comparison and treatment groups. The pre- and post-assessment items were designed and administered to evaluate student thinking of earth and environmental science, computer science and mathematics.

The pre- and post-assessment results were collected and analyzed using statistical inferences. Students are clustered under each teacher. Each teacher has several treatment groups and one comparison group. Students' demographic variables, such as gender and ethnic groups, are included.

In addition to the pre- and post-assessment, we used the Upper Elementary (4-5th) and Middle/High School (6-12th) S-STEM Surveys (Friday Institute, 2012) to measure students' confidence and efficacy in STEM subjects, computer technology, 21st century learning skills, and interest in STEM careers. In this paper, we present three simulations we designed for two modules, namely the Shadows and Time module and the Greenhouse Effect module, and present our findings from the assessment and survey items.

Simulation Design

Netlogo is a multi-agent programmable modeling environment that can be used to design dynamic simulations of various complex phenomena (Wilensky, 2006). The animated outputs and result plots of Netlogo can help students understand the evolving dynamics of the interactive simulations and the phenomena they model. According to Arshavskiy (2013), the benefits of simulation-based learning include the following:

- *Active engagement:* The simulations allow students to get actively involved in the learning process by interacting with the interface.
- *Adaptability*: A "try, fail, learn" experience is very beneficial for students to develop critical thinking skills through adaption to the real world.
- *Self-paced*: The pace of traditional learning is set and fixed by the teacher. With the simulations and some web-based platforms, students can adjust the pace of the learning based on their progress and schedule.
- *Quick feedback*: The online-based practice can give students immediate feedback. For traditional learning, students usually have to wait for teacher's grading and feedback.
- *Cost-effective*: Simulations are very cost-effective and can be distributed easily.

One of the goals of our design was to infuse regional phenomena observed in the local communities into the simulation. The purpose was for the students to examine how their own city and local community can be affected from the environmental changes.

1. Shadow and Time

The Shadows and time simulation is an interactive Netlogo simulation in which one can explore the relationship between the length of the shadow and time. The simulation is relevant to the Next Generation Science Standard (NGSS) *5-ESS1-2* "*Represent data in graphical displays to reveal patterns of daily changes in length and direction of shadows, day and night, and the seasonal appearance of some stars in the night sky*." It is also aligned to the Common Core State Standards for Mathematics (CCSS-M) *6.EE.C.9* "*Use variables to represent two quantities in a real-world problem that change in relationship to one another; write an equation to express one quantity, thought of as the dependent variable, in terms of the other quantity, thought of as the independent variable, analyze the relationship between the dependent and independent variables using graphs and tables, and relate these to the equation*" and *7.RP.A.2 "Recognize and represent proportional relationships between quantities*."

In the user interface, the "Change time of day" button is used to choose a different time of the day while three monitors show the length of the object, shadow and angle of the sun. Users can choose a specific object of their interest, such as a house, a person, or a tree for display. Then they can move the slider to select a particular time of the day. Users can choose the time of the day between 6 am to 6 pm in a slider. The length of the shadow on the simulation would vary based on the chosen time. The heights of the object and the shadow of the object as well as the angle of the sun relative to the ground are also displayed. By manipulating the variables on the simulation and observing the change, users can recognize that the shadow moves in the opposite direction relative to the sun. They can also make generalizations about how these variables affect the length of the shadow.

There are many existing simulations, videos, games relating to the topic of shadows and time, however, most of these do not include the length of the shadow as the learning objective. Additionally, most of them are not very interactive. This simulation is engaging, interactive, and easy for users to manipulate and check their understanding.

In our simulation, the goals are for the students to learn the concepts and interrelation of the position, deformation, length of the shadow and time. The equation of $L = h / \tan(\alpha)$ was used to calculate the length of the shadow, with L being the length of the shadow, h being the height of the object, and α being the angle of the sun relative to the ground. Fig. 1 displays a snippet of the code and Fig. 2 shows a screenshot of our shadow and time interface.

Figure 1. A snippet of the code for shadow and time simulation.

We integrated the simulation into an instructional module that engages students in a series of investigations that include exploring the simulation, reasoning about the dependent and independent variables of the phenomenon, collecting data based on the simulation, graphing their data and making generalizations about the relationship between the length of the shadows and time. In terms of mathematical thinking, the specific module focuses on collecting data of the length of shadow over a specific time, plotting the ordered pairs and constructing non-numeric and numeric relationships about the quantities that co-vary, for example as the time changes, the length of shadows changes, or recognizing that from sunrise until noon, the angle of the sun increases while the length of shadow decreases while from noon to sunset, the angle of the sun increases while the length of the shadow increases.

Figure 2. A screenshot of our shadow and time simulation interface.

2. Sea Level Rise

The goal of the Sea Level Rise simulation is for the students to learn about the effects of global warming from the excess greenhouse gases and how it impacts the sea level rise. It is aligned with the NGSS ESS3.D on Global Climate Change. In this simulation, the user has control over the average rise in global temperature, which can be increased from 1 to 5 degrees.

While there are many other simulations of sea level rise, most focus on a satellite map view of flooding, which is not very intuitive for students to understand. Our simulation utilizes various cartoon buildings in different areas of the New York city, Newark and Kearny and shows how these buildings will be flooded by water. We use Global Cities at Risk from Sea Level Rise (2015) data, whereby average sea level rises by 4 feet per 0.5 degree Celsius increase in temperature. As the user moves the temperature slider from 0 degrees Celsius to 5 degrees Celsius, one will notice that the sea level rise goes from 0 feet to 40 feet. Due to the different elevation of downtown Manhattan, East Newark, Newark and Kearny, users can observe when each region will be submerged by the rising sea in order. For instance, downtown Manhattan has the lowest elevation of 10 feet above sea level while Kearny has the highest elevation of 108 feet above sea level. Fig. 3 shows the code to compute the sea level based on the current temperature.

The interface presented in Fig. 4 has a slider to control the temperature rise as input and one output box as sea level rise. More buildings and cities are flooded as a higher temperature rise is selected.

Figure 3. Partial Netlogo code to compute the sea level based on temperature.

This simulation is integrated into the Greenhouse Effect module. We designed an investigation in which students are asked to explore the simulation, manipulate its variables and construct a relationship between the height of future sea level, the total remaining land area and the global temperature rise. We designed these relationships to be linear in order for the students to make generalizations such as the global temperature increases, the height of sea level increases or, the higher the height of the future sea level, the less is the remaining land area. Additionally, we ask students to collect data based on the simulation and analyze the quantities numerically. For example, observing that as the global temperature is decreasing by 1, the height of the future sea level is decreasing by 8 feet. This investigation also includes a discussion about the risk of going under sea water of different cities. By exploring the simulations, students can generalize that the higher the elevation of a place, the lower the risk of going under sea water.

Figure 4. An interface of the sea level rise simulation with the rising temperature.

3. Carbon Dioxide Calculator

The goal of the Carbon Dioxide Calculator simulation is to help students become aware of their carbon dioxide (CO2) footprints from their daily activities. Many of our daily activities, such as driving a car, using the computer, and turning on the air conditioner (AC), release certain amount of CO2 into the air. Carbon dioxide is one type of greenhouse gas, which keeps the earth warm by absorbing the sun's energy. The excess amount of CO2 can trap more solar heat and cause melting of ice caps on the poles and rising of ocean level. This simulation computes the total amount of carbon dioxide based on the life pattern the user chooses (Carbon Calculator from Nature). By engaging with this simulation, students explore what they can do to reduce the greenhouse gas and also examine relationships between the quantities that are included in the calculator. This simulation is aligned to NGSS *ESS3.C* on the human impact on Earth systems and CCSS-M *7.RP.A.2* on recognizing and representing proportional relationships between quantities.

The simulation includes daily activities, such as watching TV, using computer, taking bath or shower, turning on AC or heater and transportation. As users choose different options, the monitor on the interface labeled "CO2 (kg/year)" dynamically computes and shows the value of the CO2 generated. There is also a bar that visually elongates as the value of CO2 increases. Different colors are used depending on the amount of CO2. Green means recommended amount, yellow means warning, and red means high amount. This simulation also shows graphic icons reflecting the activities chosen. For example, if the TV option is turned on, a TV will be displayed inside the house. The transportation vehicles and carpool number of people are also displayed. Fig. 5 shows the interface of CO2 gas calculation for daily human activities.

Our goal is to familiarize the students with some possible green ways that they and their families can do to reduce humans' footprints on the planet. For instance, for every kilometer driving without any carpool, the system adds 167 kg of CO2 per year. If one takes a bus or a train every day, this action adds 87 kg of CO2 per year. Walking and biking do not add any CO2. A code example of calculating CO2 in terms of TV usage is shown in Fig. 6.

Figure 5. The interface of CO2 gas calculation for daily human activities.

Figure 6. Part of the Netlogo simulation code for CO2 gas computation.

This simulation was integrated into a module on the phenomenon of the Greenhouse Effect. For this specific simulation, we designed two investigations in which students explored the simulation with its variables and collected data. Students studied the covariation relationships between various activities and the amount of CO2 generated and made generalizations. As a simplified design approach, we made those variables to increase in a linear fashion in order for the students to recognize a simple linear relationship between those quantities (e.g. hours of TV) and CO2 released. In that way, the students are able to construct numeric covariation relationships among quantities, such as if I double the hours I watch TV, the amount of CO2 that is released in the atmosphere is doubled. After exploring those relationships, students are asked to use the simulation to collect their own data based on what their own daily activities are and suggest possible behavior changes that they could do in order to reduce the amount of CO2 released in the atmosphere.

STEM Interest Survey and Assessment Analysis

Before we give the simulation-based lesson modules to our students, we distributed the STEM survey (Friday Institute, 2012) to evaluate students' general interest in STEM and computer technology. Additionally, as aforementioned, we administered a pre- and a post-assessment before and after each module. In this paper, we present a sample of our ongoing analysis to illustrate some of our preliminary results.

1. Boys and Girls interest in Computer and future jobs

Prior to imparting the simulation lessons, we conducted a STEM survey to assess students' interests in Computer Science. We were interested in assessing whether gender played a role. In order to test our hypothesis, we did a two-proportion z test using R language as the following:

Our null hypothesis is that the proportion of boys who like computer is equal to the proportion of girls who like computer. Our alternative hypothesis is that there is a significant higher proportion for boys who like computer than girls. The significant level is set at 0.05 and we used a one tailed test. Out of 46 boys, 29 of them said they love computer. Out of 40 girls, 18 of them said they love computer.

H_0: p(boys like computer) - p(girls like computer) = 0
H_a: p(boys like computer) - p(girls like computer) > 0
alpha = 0.05

We used the question "Do you like computer?"

The following R source code for our two-proportional z test on the gender difference:

n1=46 boys
n2=40 girls
phat1 = 29/46=0.63
phat2 = 18/40=0.45
pooled.phat = (29+18)/(46+40)= 0.5465
*SE(phat1 - phat2)= sqrt(pooled.phat *(1-pooled.phat))*sqrt((1/n1)+(1/n2))*
z = (phat1 - phat2 - p0) / SE(phat1 - phat2)
z = (0.63- 0.45– 0) / sqrt(0.5465x0.4535) x sqrt((1/46 + 1/40))
= 1.6729
1-pnorm(1.6729) = 0.047

From the P value of 0.047, we reject the null hypothesis and infer that there seems to be a significant higher proportion of boys who love computer more than girls.

2. Boys and Girls' confidence in Math

We also examined if there is any gender difference regarding their opinion of their math performance. To explore that, we conducted a Chi-square independence test. We used the following hypotheses:
H_0: Whether a student's opinion of their performance in Math does not dependent upon their gender.

H_a: Whether a student's opinion of their performance in Math does dependent upon their gender.

alpha = 0.05

The question we used is: "I am very good at math."

The following shows part of R the source code we wrote to analyze the dependence.

```
mathMatrix = matrix(c(R1, R2), nrow = rows, byrow=TRUE)
rownames(mathMatrix) <- c("Female", "Male")
colnames(mathMatrix) <- c("Strongly Agree", "Agree", "Disagree", "Strongly Disagree")
mathMatrix
chiResult <- chisq.test(mathMatrix, simulate.p.value=TRUE)
chiResult
```

Pearson's Chi-squared test with simulated p-value (based on 2000 replicates)

data: mathMatrix
X-squared = 1.1753, df = NA, p-value = 0.7646

Number of responses	Strongly agree	Agree	Disagree	Strongly Disagree
Female	13	10	6	5
Male	22	12	7	4

Since the p-value 0.7646 is much higher than 0.05 we failed to reject the null hypothesis. Therefore, we infer that a student's attitude about their performance on math does not depend on their gender.

3. Students' Performance in the assessments

In order to demonstrate the learning effectiveness of our computer simulation on shadow and time, we separated students who were taught by the same teacher in two groups. One control group with 13 students learned the concept using the traditional instructional materials. The treatment group with 16 students used our simulation-based instructional materials. The pre- and post-assessment scores were collected to compute the score improvement for each student. We ran two-sample t test to see if treatment group achieved average higher improvement scores than the control group.

H_0: The average score improvement for control and treatment groups are the same.
H_a: The average score improvement for treatment group is significantly higher than the control group.

alpha = 0.05

The following partial R source code shows the results of this two-sample t test:

```
results <- t.test( treatImprovelent, controlImprovement, u=0, alternative = "greater")

        Welch Two Sample t-test

data:  treatImprovelent and controlImprovement
t = 1.9928, df = 27.897, p-value = 0.02807
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 1.588555      Inf
sample estimates:
```

mean of x mean of y
9.056250 -1.803846

The P value of 0.02807 is smaller than our significant level of 0.05. We reject the null hypothesis, which suggests that the average score improvements of students using our simulation-based instructional materials is higher than the students using the traditional materials.

Conclusion and Future Plan

This paper describes our efforts for designing simulations and instructional modules that integrate Earth and Environmental Science, mathematics and computer science. We started this project less than a year ago and have successfully designed 10 instructional modules as illustrated in Fig. 7. Five of them, namely Water cycle, Greenhouse effect, Gravity, Orbit, and Shadow and Time are completed and are being tested in local schools (Zhu et al., 2018).

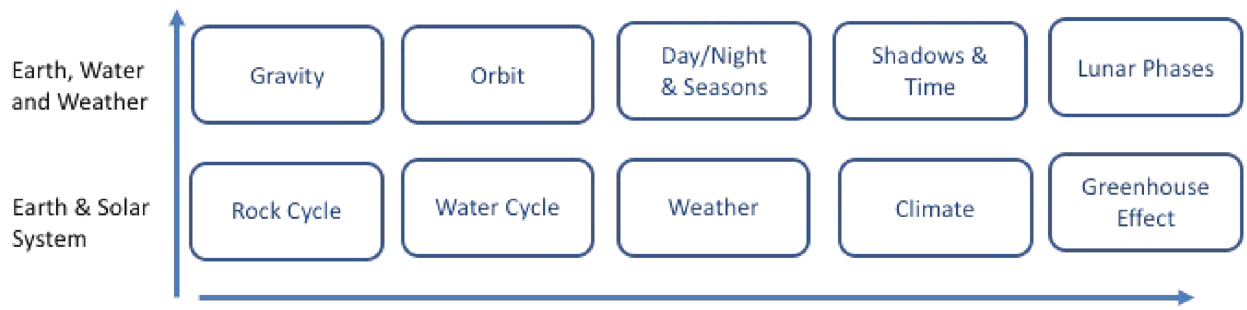

Figure 7. A table of 10 modules classified into two categories

The findings of our preliminary statistical analysis show that by engaging with our earth simulations and instructional modules, students developed their computational and mathematical thinking skills. Among our future plans are to continue revising our modules and conduct statistical analysis for the assessment results we have collected so far. Due to the gender difference, it might be a good idea to design slightly different instructional materials especially from computational aspect. For example, we may use different themes from popular movies and games to match girl and boy's different interests. We are also planning to design two more new modules focused on traffic and pollution aiming to illustrate the human impact on the environment. A short video introducing our project can be found at this NSF showcase link: http://stemforall2018.videohall.com/p/1134.

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