LEARNING THE PHYSICS OF ELECTRICITY WITH AGENT-BASED MODELS: THE PARADOX OF PRODUCTIVE FAILURE

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Abstract: The overall goal of this research is to explore the efficacy of learning the physics of electricity with NetLogo agent-based models (ABM) where the degree of learner scaffolding is varied. Learners were given four tasks for an ABM in each class period. The experimental condition involved Productive Failure (PF), where one group of learners initially used a set of ABMs in an unscaffolded manner whereas the comparison condition (Non-PF or N-PF) used a more conventional physics education laboratory approach in which the learners were provided with steps to follow in their ABM activity. Both groups then used the ABMs for a second activity that was scaffolded, followed by a third unscaffolded ABM problem-based activity that was the same for both conditions. This sequence of activities was followed over four days with four different ABMs. It was hypothesized that whereas the participants in the PF group would initially fail in the first ABM activity in contrast to the initial success of the N-PF group, by the last unscaffolded ABM activity the PF group would perform at a higher level, and that there would be cumulative overall learning gains by the posttest for this group. This paper reports on the preliminary research findings that are largely consistent with the hypothesized results. Issues for future research are also discussed.

Keywords: **Agent-based models, physics education, electricity, problem-solving, problem-based learning, collaborative learning**

1 Introduction

Theoretical perspectives in the learning sciences [1] and conventional teaching practices tend to initially provide learners with greater amounts of scaffolding that are faded over time. However, recent research suggests this "common sense" perspective may not always provide longer term and deeper learning effects [2, 3]. The overall goal of the research reported in this paper is to explore the efficacy of learning the physics of electricity with NetLogo agent-based models (ABM) [4]. We first discuss the learning context and content, followed by an overview of an emerging theory of learning—Productive Failure (PF)—that has potentially important implications for trajectories of learning and instruction [2]. This paper then describes how different levels of scaffolding were varied for participant groups learning about physics of electricity, and reports the findings to date and a consideration of provisional implications.

It is still very common to use didactic pedagogical approaches that focus on algebraic models for teaching the topic of electricity in physics [5]. Although Singapore students often conduct classroom-based electricity experiments that typically involve worksheet-oriented activities to collect data that verify, for example, Ohm’s Law or the formula for effective series resistance, the curricula materials about electricity seldom explain or make salient the underlying physical theories. It is generally accepted that many students have misconceptions and learning difficulties related to important conceptual knowledge about electricity [5-7]. Singapore students are probably no exception: a recent study found that science students who graduate from the Singapore education system tend to have strong factual knowledge about science but are weak in scientific problem-solving skills [8].

An alternative to didactic ways for learning science is to employ learner-centered approaches in which students engage in more authentic inquiry practices with scientists’ tools. The use of scientific models is an important conduct of science, and the forms of models vary depending on the types of phenomena that scientists investigate. The specific representational aspects of a system in a model can be simplified or elaborated in terms of detail or be on different scales from what is normally perceived [9]. Models are thus used to represent, explain, and predict natural phenomena. Adapting scientific models and visualization tools for education has been the focus of important research not only for physical models [10], but also for computer models [11]. Model-based inquiry [12], for example, uses a specific pedagogical approach that focuses on computer models to investigate phenomena that might be difficult to do in real school-based laboratory settings. The research to-date suggests that students using different types of models and visualizations for inquiry can lead to significant learning outcomes related to scientific knowledge and skills [13, 14]. In addition, interactive computer models that actively engage students in simulated experiments and investigations of natural phenomena may be used as a new form of assessment [15].

NetLogo is an agent-based model environment for simulating physical and social phenomena that has been under development at the Center for Connected Learning and Computer-Based Modeling at Northwestern University [4]. In this study, we used a set of models that allow participants to visualize the phenomenon of electricity at both micro (i.e., electrons propagating in circuits) and macro levels (i.e., measuring electrical quantities such as current) [16, 17]. The models are easy to use and participants may run simulations of electricity under different conditions to collect quantitative data and view graphical output.

In the present study, a Productive Failure (PF) approach [2] was used to develop learning activities involving NetLogo agent-based models of the physics of electricity. PF approach postulates that appropriately designed *unscaffolded* initial learning activities may eventually lead to more productive learning gains than scaffolded early experiences that do not allow students to fail. Research on this approach has provided evidence that that this initial failure might lead to enhanced learning and problem solving in a computer supported collaborative learning environment [2]. In this study, a PF approach was conceptualized as a way to structure a trajectory of learning activities that would enhance learning from the NetLogo electricity models.

Figure 1 is a screen shot of the NetLogo electricity model of Ohm’s Law, which shows what happens when voltage is applied to the ends of a conducting wire. This model illustrates how steady current and resistance emerge from simple interactions between electrons and atoms in a wire and battery terminals. It shows how the linear relationship between current (I), resistance (R) and voltage (V) as expressed in Ohm's Law (i.e., $V = I * R$) emerges from these nonlinear micro-level interactions. Instead of viewing current and resistance as an aggregate phenomenon as done in traditional teaching and laboratory settings, students can observe the behavior of electrons by varying model parameters in order to explore questions such as the relationship of voltage to electron velocity in a conductor or current to the number of electrons[1].

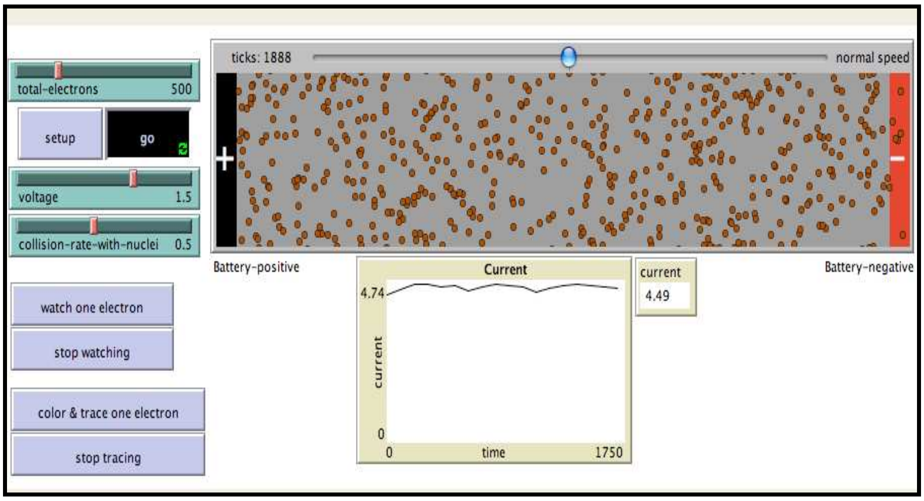

Figure 1. NetLogo model of Ohm's Law

2 Method

We developed experimental materials for learning activities involving four NetLogo models: Coulomb's Law,[2] Ohm's Law, series circuit, and parallel circuit [16, 17]. For every model, three problem-based activities were prepared for the PF and N-PF conditions. The experimental design for the study is shown in Table 1. The learning materials for PF condition may be viewed as a subset of N-PF learning materials. The two conditions only differed in scaffolding structures in activity 1.

Table 1: Instructional Sequence

	Activity1	Activity 2	Activity 3
PF	Not Scaffolded	Scaffolded	Not Scaffolded
N-PF	Scaffolded	Scaffolded	Not scaffolded

Activity 1 (N-PF): This scaffolded activity for the N-PF condition was designed to help participants focus on and learn important ideas in the particular model they were working on. For example, as shown in Table 2, participants were given three parameter relationships to explore consisting of an independent variable and two dependent variables and a minimum number of readings to collect data that would be necessary to determine important relationships between these variables. This activity was intended to be similar to conventional electricity experiments done in a typical school physics laboratory. After completing this scaffolded activity, the participants were asked a couple of open-ended questions, such as for model 2 (Ohm's Law): How would you describe the effect of collisions on current? Why is it so?

[1] Note that the number of electrons and velocity are more concrete concepts than current and resistance that are abstract in nature.

[2] The current curriculum units on electricity in Singapore do not include Coulomb's Law at the secondary level. However, the NetLogo electricity models used in this study follow rules of behavior as governed by Coulomb's Law, so we included this topic in the experimental materials

Table 2: Relationship between Collision Rate and Current

Collision rate with nuclei	Time taken to reach battery negative to battery positive	Current
0.5		
0.7		
1.0		

Activity 1 (PF): The PF group was provided with the same question as the N-PF group, but without scaffolding of any kind. The participants needed to decide on the set of variables to work with in order to answer the question. It was expected that the participants would first struggle to select appropriate dependent and independent variables as they used the NetLogo electricity model to make predictions and observe the behavior of the model in the animated visualization and the graphical output.

Activity 2. This scaffolded activity was patterned after Activity 1 for the N-PF group, but was the same for both the N-PF and PF conditions. The participants completed a scaffolded "worksheet" type of activity trying out different parameter relationships with the NetLogo model being used followed by answering an open-ended question based on the activity.

Activity 3. This non-scaffolded activity was identical for both treatment conditions and was patterned after Activity 1 for the PF group. The participants were asked open-ended problems that were intended to help synthesize and extend the learning from the two previous NetLogo-based activities, such as:

1. *From activities 1 and 2, can you infer relationship between the voltage and velocity of electrons?*
2. *In the NetLogo unit you ran, you may have noticed that there is no slider value "0" for collision rate with nuclei. Why?*

3 Research setting

This study was conducted at two secondary schools in Singapore. School A was ranked by the participating teachers as having participants with middle to high range achievement, whereas participants at School B were ranked as being middle to low in their academic achievement. A total of 142 participants in secondary four (grade 10) classes from the two schools. Participants in both schools were randomly paired and each pair was assigned to one of the two conditions: Productive Failure (PF) and Non-Productive Failure (N-PF). School A had 16 pairs of students in the N-PF condition and 15 pairs in the PF condition, and School B had 20 pairs in the PF condition and 20 pairs in the N-PF condition. Three pairs of participants from each condition were selected based on their test scores (high, medium, and low) to collect process data as they worked with the NetLogo models using screen capturing software and webcams for video and audio recordings of the participants working together.

The intervention was carried out in the computer laboratories of the respective schools. Each pair of participants shared a computer to run the NetLogo agent-based models (ABM). The experimental materials had three activities that lasted approximately 20 minutes each (see above) over a one-hour period. The participant pairs worked collaboratively though the first two activities, while the teacher and researchers monitored the sessions and were available if there were technical problems or questions about running the software (but not to answer content related questions). The participants were allowed to discuss with their partners in activity 3 but wrote down answers to the problems individually.

As 12 participants did not complete all of the activities and assessments, the final data analysis was done with 130 students who completed both the pretest and posttest; of which 63 were in PF and 67 were in N-PF conditions. The pretest consisted of 30 validated items that were selected to test for factual knowledge, conceptual understanding, and scientific reasoning about static electricity and current electricity topics in physics. The posttest consisted of 34 items, with 26 items from the pretest, four parallel version items similar to pretest items, and four within domain transfer items (i.e., electricity concepts related to but not directly worked on in the treatment materials). A physics content expert examined the pretest and posttest items and established their content validity. Focus group interviews were carried out with the same participants recorded during the four sessions of the study.

4 Results

Given space limitations in this paper and the ongoing analysis of the data, we can only report on the analysis for school A on the multiple choice and short answer items. There were 10 conceptual factors reflected in the assessment items. However, two of the factors were statistically unreliable, so the primary analysis reported here is on the remaining eight conceptual factors: Coulomb's force, characteristics of electrostatic force, Bohr's model, circuit characteristics, conservation of charges, effect of series and parallel connections on bulb brightness, resistive circuits, and open and closed circuits.

Table 3. Total Scores and ANOVA Results for School A

	Productive Failure (P)			Non-Productive Failure (N-PF)		
	Pre	Post	Difference	Pre	Post	Difference
Mean STD	54.6 (16.6)	66.7 (15.2)	12.1 (17.2)	64.4 (13.3)	59.9 (17.3)	-4.6 (22.3)

Table 3 shows the total weighted scores and standard deviations of PF (Productive Failure) and N-PF (Non-Productive Failure) groups in school A for the pretest and posttest. Each factor was assigned a maximum score of 12.5, which made the total maximum score equal to 100. The N-PF group had a significantly higher average score on the pretest ($F(1, 55) = 5.68$, $p=.021$), however the PF scored at a higher level on average on the posttest. A difference score (posttest – pretest) was calculated that showed the N-PF group declined -4.6 points (non-significant difference) by the posttest, whereas the PF group gained 12.1 points. This was a significant difference between the two groups on the mean difference score ($F(1, 54) =10.67$, $p=.002$, $\eta^2 =.165$) with a large effect size.[3]

Given the significant learning gains of the PF group, we were interested in looking at the interviews for possible factors that might have contributed to the learning differences between the two experimental groups. Focus group interviews for six participants from PF conditions and six participants from N-PF conditions in school A were conducted and transcribed. Here we report interview excerpts from school A. Participants in both treatment groups indicated that they liked learning with the NetLogo models because of the visualization affordances for micro-level behaviors of electrons. One participant, from the PF group, expressed this idea in this way:

[3] A partial η_2 = .01 is considered a small effect size, .06 medium, and .14 a large effect size.

Yeah, I think I'm better able to visualise and conceptualise the idea of electricity, because, ah, previously in Secondary 2 when I learnthe electricity I could only learn it in terms of text and formulas. … It's very hard for me to visualise how actually, how the, it's very hard for me to appreciate the formula in that sense, like how, how the, how the different elements are related. But with the … NetLogo model I am better able to see how it actually connects.

Another participant from the PF group described how he worked collaboratively with his partner and tried to explore various possibilities since the first activity was unscaffolded.

Because some worksheets was not very specific-la. So we were discussing whether which of variable should be kept constant and which one is should be changing so that we can answer the question-la. So before we shift the sliders my partner and me will try to hypothesize, like oh this is directly related to that or in equal-proportion-to-that, so-we-try-to-slide. But in the end all our assumptions were wrong and then we couldn't find any relations so we keep shifting the sliders and then we were discussing, ah, why are the results are inconsistent with our assumptions and stuff.

These comments illustrate the notion of "failure" the PF participants typically experienced during their initial non-scaffolded problem activity with the NetLogo electricity models. In this excerpt, however, the participant did not seem discouraged by these unsuccessful pursuits.

Surprisingly, the interviews with participants from the N-PF group (who received a much more carefully scaffolded set of instructions about how to accomplish the initial problem activities with each model) suggested they felt frustrated by the end of the module:

We, ah, me and my partner asked [the teacher] to clarify some, clarify, some stuff about the model in question. I prefer that she teach. It's much more... It will clarify more things that she, than she...eh, if she teaches.

This participant (and other N-PF participants who were interviewed) did not feel he had learned the material very well, and so he believed he still needed more direct teaching support from the teacher. This was in sharp contrast to the PF participants who did not mention in the interviews any desire to have the teachers "teach them" beyond what they had experienced with the PF learning materials.

5 Discussion and Conclusion

Our preliminary findings based on the multiple choice and short answer pretest and posttest questions indicate that participants in the PF condition learned more than the participants in the N-PF condition. Our results are consistent with those reported by Kapur [2]. We had hypothesized that the PF students would struggle to explore different ideas and approaches for solving the unscaffolded initial problem for each of the four NetLogo models during activity 1. In doing so, they may have activated their prior knowledge[4] and cognitively explored a wider range of ideas and concepts than the N-PF students who merely followed the “worksheet-like” scaffolded set of activities with the NetLogo problems. Consequently, the PF students’ experience of exploring a larger problem space may have allowed them to activate a number of ideas beyond what is needed to solve the initial problems for each model. This, in turn, may have increased their capacity to learn from the subsequent scaffolded model-based problems, even if the PF participants did not correctly solve the initial model problem (as suggested in the interview above). The PF participants thus may have been more “cognitively primed” to learn from the second set of scaffolded model-based activities, and the third unscaffolded activity, i.e., better prepared for future learning [18]. Given the strong significant findings of the higher performance of the PF group compared to the N-PF group on the posttest, we conclude that there was a cumulative efficacy of the PF learning activities over the different NetLogo model units that the participants completed over the four days.

The interviews also suggest that the participants in the PF condition were working with models more like experts and collaboratively performed their tasks as a group. The N-PF participants, on the other hand, were often observed to ask the teacher for answers (which were not directly answered) rather than exploring and investigating the phenomenon themselves as scientific inquiry. Perhaps the availability of scaffolding in the instructional materials at the initial and middle stages made the N-PF participants dependent on the scaffolding in order to know what to do, in contrast to the PF participants who demonstrated more perseverance and self-reliance.

We are in the process of analyzing a set of more conceptually challenging open-ended problems the participants worked on. We also plan to look at screen recordings with webcam video and audio recordings taken of a subset of the participants that may provide us with further insights into the dynamics of “productive failure” learning activities (that paradoxically lead to productive learning outcomes) and the “non-productive successes”[5] of the “non-productive failure” group. There clearly are a number of issues to explore related to this notion of productive failure that we plan to investigate further in the ongoing analyses of data collected in this study. In addition, future research is warranted and needed in order to consider the potentially important theoretical and applied implications of this approach.

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