

PhET Simulations in Undergraduate Physics: Constructivist Learning Theory in Practice



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Mary Gene Saudelli^{1*}, Robin Kleiv^{2*}, Jessica Davies^{1*}, Martin Jungmark^{1*},
Rebecca Mueller^{1*}

¹ *University of the Fraser Valley*

² *Thompson Rivers University*

Abstract

Simulation educational technologies provide a convenient way to augment classroom learning in higher education. The University of Colorado Boulder has created many Physics Education Technology (PhET) computer simulations relevant to concepts in Sciences and Mathematics. There is a notable gap in the literature of simulation-based technologies, learning theories, and Physics pedagogy in higher education. This action research study addresses that gap by exploring the role of the intentional inclusion of PhETs in the teaching practice of an undergraduate Physics class in a Canadian university. The professor of PHYS 105 taught a class of 80 students (primarily non-Physics majors) and integrated PhETs throughout his lesson plans during the semester to see if they supported students' learning of the Physics concepts. Findings indicate that PhETs have value as a "more capable peer" in Vygotsky's (1978) zone of proximal development. Findings indicate that PhETs are a valuable bridge between classroom learning and the laboratory learning experiences in a Physics higher education course.

Keywords: simulation-based teaching, Physics pedagogy, PhETS, constructivist learning theory, zone of proximal development

*mary.saudelli@ufv.ca

*rkleiv@tru.ca

*jessica.davies@abbyschools.ca

*martinjungmark@hotmail.com

*rebecca@themuellers.io

Computer simulation educational technologies provide a convenient way to augment experiential learning during laboratory experiments. Simulation technologies have been studied in higher education classrooms in disciplines such as medicine (e.g., Al-Elq, 2010), nursing (e.g., Kim et al., 2016), and chemistry (e.g., Chang, 2017), yet there is a notable gap in the literature on simulation-based technologies, learning theories, and pedagogy in relation to teaching Physics in higher education. This action research study explores the intentional inclusion of Physics Education Technology (PhET) in the teaching practice of an undergraduate Physics class in a Canadian university. The University of Colorado Boulder has created PhET computer simulations relevant to concepts in Physics, Chemistry, and Mathematics that are freely available online under a Creative Commons license.

Although the context of this study is a university in British Columbia, the implications from the findings can impact teaching Physics in higher education across Canada. The study's principal researchers encompass: the "professor" (a higher education Physics professor); the "collaborative friend" (a faculty member in the Teaching and Learning department of the same university); and three "research assistants" (all of whom are upper year Physics students at the same university at the time of this study).

The Physics professor had taught this course several times previously, predominantly using a lecture method of instruction. He noted that many students, especially those who were not Physics majors, felt uneasy about Physics education and Physics concepts. This represented an aspect of his pedagogy that was disconcerting to the professor. To address this problem, he intentionally integrated PhET simulations in PHYS 105 to change his teaching practice and maximize students' opportunities for experiential learning. The professor thought the inclusion of PhET simulations would enable students to visualize Physics concepts in a meaningful manner and thus provide a better learning experience. The purposes of this study are to explore the nature of this change in this professor's pedagogy, uncover students' voices in relation to the change in pedagogy, and learn about simulation-based pedagogy as related to social constructivist (Vygotsky, 1978) and experiential learning (Jarvis, 2012) theories in Physics higher education teaching practice.

Constructivist Learning Theory and Literature

Constructivist learning theory states that learning is subjectively constructed when learners interact with sensory information through "examination, questioning and analysis of tasks and experiences" (Applefield et al., 2001, p. 40). Learners' experience with and interpretation of sensory information (Jarvis, 2012) allows individuals to create an internal mental model (Henderson et al., 2002). PhET computer simulations follow a constructivist approach in terms of their design (Finkelstein et al., 2006). When students can explore within interactive computer simulations, they construct their understanding through the experience of using and manipulating the PhET (Wieman & Perkins, 2006, p. 290).

Vygotsky's (1978) zone of proximal development (ZPD) is a conceptual space that exists between states where tasks are too challenging for an individual to complete independently and those which the individual can complete autonomously (Kapon, 2016). Tasks that require assistance to complete show the highest potential level of conceptual sophistication the learner can achieve (Verenikina, 2010); tasks that the learner can complete without assistance show the lower potential level of conceptual sophistication the learner can achieve.

Research on ZPD has predominantly explored situations in which teachers or other students take on the role of the "more capable peer" (Vygotsky, 1978) in collaborative learning (e.g., Roberts, 2016; Saudelli, 2014). Concepts central to the role of a more capable peer include: visual representation and mental models, facilitative models of learning (discovery), and scaffolding the learning. Visual representations and mental models are vital to students' deep understanding of Physics concepts (McKagan et al., 2008). PhET simulations support this type of learning through their visuals and their interactive nature (McKagan et al., 2008; Wieman & Perkins, 2006). In Physics, students often learn about phenomena that are not directly observable (such as electromagnetic fields) nor visible to the naked eye, such as electrons. PhET simulations aid student learning by making the invisible visible (Wieman & Perkins, 2006).

As students learn through virtual experimentation, they build internal mental models that explain their observations (Henderson et al., 2002). In typical lecture style classes, the instructor is unlikely to detect if students incorrectly learn something and are therefore building faulty models, whereas incorrect mental models are immediately targeted when students use computer simulations (McKagan et al., 2008, p. 415). Therein lies the importance of the concept of "runability," which refers to our use of mental models to "test out possible outcomes in advance of some action" (Henderson et al., 2002, p. 1). Before students manipulate features in a simulation (or any other situation), they are running their mental model, which is a "dynamic process of building, running, and perhaps then changing, the internal mental representation" (Henderson et al., 2002, p. 1). When students manipulate variables and observe the effects in real time, they visually observe the differences or similarities between the prediction produced by running their mental model and the accurate outcome of Physics principles shown in the simulation.

Finkelstein et al. (2006) assert that PhETs use an interactive approach, employ dynamic feedback, follow a constructivist approach, and make explicit otherwise inaccessible models or phenomena. Considering the central concepts of ZPD, McKagan et al. (2008) discuss the potential for experiments and labs to cause problems for students trying to learn about a specific Physics concept due to extraneous complications of the environment and equipment. PhET simulations can avoid real-world effects and distractions, which are not directly relevant to the Physics concepts, thereby focusing attention only on the Physics concepts at hand

(Wieman et al., 2008). Moreover, PhETs explore unreal scenarios that cannot be reproduced in the classroom or laboratory experience; for instance, changing the strength of or completely removing gravity as in the Gravitational Force PhET, allowing students to test their mental model in more scenarios (Wieman et al., 2008).

The increased prevalence and importance of digital learning tools give rise to our guiding research question: What can be learned from changing teaching practices to integrate PhET simulations in an undergraduate introduction to Physics class delivered to predominantly non-Physics major students? This question frames this participatory action research study of a professor changing his teaching practice to include PhET simulation-based learning in an undergraduate Physics class.

Research Design

Participatory action research is an important qualitative research methodology. For the purposes of this study, participatory action research is defined as “a philosophical approach to research that recognizes the need for persons being studied to participate in the design and conduct of all phases (e.g., design, execution, and dissemination) of any research that affects them” (Vollman et al., 2016, p. 129). Kemmis and McTaggart (2005) assert that “The combination of practice change and collaborative research ... is possible and makes good sense. ... Participatory research, in particular, shifts the emphasis from action and change to collaborative research activities” (p. 563). Thus, participatory action research represents a collaborative, systematic, and reflexive process of inquiry into practice that directly involves a dual role for the participants: researcher and participant. It involves a cyclical process of “research, reflection, and action” (MacDonald, 2012, p. 36).

In this participatory action research, the Physics professor changed his pedagogy for an Introductory Physics course from his lecture-style approach to one that incorporated the use of interactive PhET simulations available from the University of Colorado. The research question guiding this study is: What can be learned from changing teaching practices to integrate PhET simulations in an undergraduate introduction to Physics class delivered to predominantly non-Physics major students? This research question involves the following sub-questions: Do PhET simulations have the potential to support student learning of Physics in higher education? Can digital learning tools such as PhET simulations be used as “more capable peers” for students in a learning activity? To that end, it was anticipated that this research study would edify the nature of this Physics professor’s experience of pedagogical change from a lecture-based approach to one that supports a constructivist pedagogical approach.

Data Collection and Analysis

Classroom-based, participatory action research involves the use of “qualitative interpretive modes of inquiry and data collection ... with a view to teachers [and professors] making

judgments about how to improve their own practices” (Kemmis & McTaggart, 2005, p. 561). The professor has the dual role of researcher and participant in this study; he is simultaneously the instructor delivering the course and the researcher investigating a change to his teaching practice. Hence, it is crucial to include a participatory team approach to data collection and analysis, and to the communication of the results of the study.

In participatory action research, “primacy is given to the teachers’ self-understandings and judgements” (Kemmis & McTaggart, 2005, p. 561). Thus, data consisted of the professor’s journal entries, lesson plans, and all textual materials related to this change in his pedagogy. A colleague from the Teaching and Learning Centre is the collaborative friend (Kemmis & McTaggart, 2005) who provides feedback and comments to the professor. Data also consisted of students’ anonymous survey responses as well as debriefing notes among the researchers (professor and collaborative friend) and three upper-year undergraduate research assistants.

Data analysis is constant comparative (Creswell, 2009), and followed the Kemmis and McTaggart spiral of action research (Kemmis et al., 2014). As the researchers collected, categorized, and discussed the data, they followed the think, plan, act, think spiral of data analysis. Coding followed Saldana’s (2016) process procedure of analytical, qualitative coding. Three full coding processes were achieved to uncover findings, patterns, and themes to satisfy qualitative credibility among data sets (Denzin & Lincoln, 2005).

Research Ethics and Limitations of the Study

This participatory action research study received clearance from the institution’s Research Ethics Board (File #938T-17). This study is subject to the limitations of any qualitative study: It does not intend to generalize or suggest any form of causal attribution; rather, its purpose is to explore teaching practice.

Findings

The study’s findings fit the overarching theme of PhETs as a more capable peer in Vygotsky’s (1978) ZPD; the findings describe the PhETS, their usage in teaching practice, and how PhETS address the ZPD concepts of providing a visual representation and mental model of the Physics concepts that can be discovered, sensed, and manipulated by students who construct learning based on the PhET response to their use of the tool. The findings are presented as: The Context: PHYS 105, and descriptions of observations in chronological order of the classroom experience.

The Context: PHYS 105

The introductory Physics course had 80 students registered for attendance and the assigned classroom was a typical theatre-style lecture hall. The chairs were in rows across the centre of

the room, which made access to electrical outlets problematic. As the seats were 30 across, it was awkward for the professor to walk around the students to assist when he had them engage in learning tasks. From the beginning of the study, the professor believed that students would find PhETS visually appealing and enjoyable. He also felt PhETS might be a positive way to address the anxiety he had observed in students who were non-Physics majors.

Some PhETs are more interactive than others, and some are dynamic in different ways, which offers different learning potentials and possibilities. As students engage with the PhETS (manipulate their systems and settings to see what happens within the PhETS), they can make observations and form mental representations of Physics concepts. For example, the following PhETS were used in the PHYS 105 course: Circuit Construction Kit, Waves on a String, Masses and Springs, Hooke's Law, Sound, Wave Interference, Bending Light, Geometric Optics, States of Matter, Blackbox Spectrum, Gas Properties, and Energy Forms and Changes (PhET Usage Plan, January 22, 2017).

Students supported the use of PhETS: "Knowing beforehand that we were going to use PhET the next day made me look forward to it (and I never thought I would look forward to Physics)"; "they were helpful"; "fun to use"; and a "good substitute for regular lecture" (April Student Survey). In addition, students positively reacted to a question on the April survey to indicate that they used PhETS outside of class for both homework and fun. Students noted that they used PhETs to help with assignments, such as: "circuit building and with the circuit building assignment"; "the wave assignment"; and "to visualize the collision lab" (April Student Survey). They further indicated that PhETS "helped me correct my work" and "I enjoyed manipulating variables and observing consequences on my own. It was fun"—with the two favourite PhETs being "Waves on a String and Circuit Builder" (April Student Survey). There were also some "anti-favourite" PhETs for students, including Black Body Spectrum (for most students, although two students liked it and one chose it as a favourite) and States of Matter, which was deemed "harder to understand" and "not very interactive." In the collaborative friend debriefings, discussions related to students' enjoyment focused on opportunities for students to "visualize and play" but also on pedagogical decisions guiding PhET choices; their pedagogical use as illustrative, demonstrative, or interactive; and why a faculty member might choose one PhET or another for its learning potential of Physics concepts.

The findings represent that the decision-making process underpinning PhET selection is important and includes considerations such as: relatability to the Physics concepts, learning level of the PhET, visual representation, and the interactive nature of the PhET. The professor disclosed that PhETs fit "a nice space between lecture and lab" (Reflection, January 20, 2017), a theme that was revisited throughout the data.

January 20, 2017 Class

This class focused on the Physics concepts of spring force, weight, and Hooke's law. The professor introduced the PhET Masses and Springs. In this PhET, students were able to attach a mass to a spring, measure displacement using a ruler, and measure the oscillation period using a stopwatch. Many parameters are adjustable in the PhET, such as the acceleration due to gravity which would be nearly impossible to change in a real experiment.

The professor instructed students to try it before class as a pre-learning activity and bring an accessible device with the PhET to class as the Physics concepts of spring force, weight, and Hooke's law represented new material for students. The Physics course explores simple harmonic motion (SHM) prior to applying it to the Physics concept of waves. The course does not include Newton's laws of motion, which are usually discussed before SHM in Physics.

The expectation was that students would engage with the PhET as a form of scaffolded exposure to the Physics concepts through direct interaction with the PhET and that the in-class element would reinforce the learning with the PhET and a collaborative discussion activity (Reflection, January 20, 2017). As an added incentive, students were informed this would make an appearance on an upcoming assignment. In this manner, the PhET served two purposes: (a) pre-learning exposure to scaffold learning and allow students to build a visual representation of the mental model, and (b) a more capable peer in the pre-instructional exercise, allowing for a scaffolded approach to learning Physics concepts.

The result in the classroom was that students "intuitively understand but the mathematical description of the Physics concepts was missing and needed reinforcement in the class" (Reflection, January 20, 2017). The professor observed that students were actively engaged in working with the PhET in class, and seemed to enjoy it (Reflection, January 20, 2017). The professor also noted that the PhET "Addressed a gap in students' knowledge, but also helped develop students' Physical intuition, e.g., their intuitive understanding of physics concepts. Students tried working with the PhET and perhaps intuitively developed that Physics reasoning – a subconscious development of the mental model" (Reflection, January 20, 2017). This observation was supported by students who made the following comments: "The simulations make the Physics concepts easy to understand by conveying them in a visual way" and that they are a "Fun and interactive way to make learning Physics more of a visual experience, which really helped me get it" (April Student Survey).

January 27, 2017 Class

The January 27, 2017 class focused on the Physics concepts of Hooke's law. The Hooke's law PhET allows students to apply a force to a spring with one free end and displays vectors for the applied force, spring force, and displacement. The simulation displays dynamical, real-time

graphs showing the relationships between the applied force, spring constant, and potential energy. The Hooke's law PhET provides a visualization of the mathematical relationship of Hooke's law.

The professor noted that this PhET was “stripped down of complications and spoke to core Physics concepts” but noted his concern that the way he used PhET seemed “passive” thus questioning the learning value for students (Reflection, January 27, 2017). The professor noted that in the future it might be worthwhile to assign this PhET as a “pre-class activity on forces [and] Newton's law[s]” to provide the schema for the mental model (Reflection, January 27, 2017). Using the PhET in class, the professor noticed that this PhET was more effectively used for demonstration purposes (Reflection, January 27, 2017).

The collaborative debriefing discussed this aspect of the learning and noted that this “PhET provides a demonstration that is dynamic but not interactive. It is concept heavy but allows students to internalize and visualize—which builds that mental model to relate Physics concepts to the real world” (Collaborative Friend Debriefing). The research assistants noted that “Often students memorize the equation then have difficulty with the Physics concepts because [they] don't understand the Physics concept the equation represents” (Collaborative Friend Debriefing). This PhET allowed students to visualize the Physics concepts behind the equations, but it was not interactive. In this way, the PhET was illustrative, which has learning potential for students in terms of refining their Physics mental models and visualizing the mental models. This is particularly relevant for real-world relevance of the Physics concepts. The students recognized the learning potential of PhETs for Physics concepts in the April Student Survey, which included many positive comments about PhETs connecting to real-life phenomena; for example: “I like putting what we are talking about and calculating in class in perspective with [the] real world. This helped me see the equation as meaning something.” Interestingly, the professor noted that he:

had the sense this PhET was different and didn't know really how to use it. It was useful to demonstrate which indicates a preconceived notion I had—it was necessary for the PhET to be interactive in order for it to be useful to refine a mental model of Physics. But, this was a powerful learning exercise for students even though this PhET was different from the others I have used. It was illustrative but not interactive. But still worthwhile and meaningful for students. (Collaborative Friends Debriefing)

In fact, this PhET “graphically illustrates how changing parameters affect the math of Hooke's law” (Collaborative Friend Debriefing)—very real-world relevance for constructing knowledge and refining a mental model for this Physics concept. Most of the PhETs that the professor utilized were “simulated experiments” deliberately mimicking the labs so that they would augment the learning experience. The professor found it easier to use those styles of PhETs rather than these “Illustrative” ones.

February 3, 2017 Class

The February 3, 2017 class used the PhET Waves on a String to teach the Physics concepts “the superposition principle, constructive and destructive interference” (Reflection, February 3, 2017). Waves are inherently dynamical, and students struggle to generalize from purely static representations of waves that are often used in the classroom. The Waves on a String PhET addresses this issue by allowing students to interact with the complete spatial and temporal dynamics of a wave. The PhET allows students to create wave pulses, travelling waves, standing waves, and to perform measurements using a built-in ruler and stopwatch. Students can be directed to use their own measurements to test physics equations such as the relationship between a wave’s speed, wavelength, and frequency.

The professor began the class with a “collaborative in class activity and questions to students” (Reflection, February 3, 2017). The professor noted one of the great values of PhETs was that “they can be used for discovery and experiential learning. I did not want everything all laid out as there is benefit from getting hands dirty—get in and discover the Physics”; the class highlighted a “discovery approach to [using] the PhET” (Reflection, February 3, 2017). The PhET supported the role of visualizing the Physics concept as students form the mental models necessary to understand. As this was ongoing, students intuitively developed Physics mental models, which was very easy to do with this PhET but would have been difficult to do in real life.

The Waves on a String PhET was one of the more interactive PhETs and was used in the course during the February 3 and February 8, 2017 classes. In the professor’s design of the lesson, he noted he would begin with a “collaborative activity and questions to students” (Reflection, February 3, 2017). He noted that students seemed “engaged, interested, seemed to enjoy this PhET, and students seemed to trust” the Physics concept; the PhET was “great, robust with the strongest students picking it up immediately and then continuing to manipulate the simulation” (Reflection, February 3, 2017). This observation led to comments among the collaborative friend and research assistants regarding the nature of this Physics concept being “Dead easy to do in simulation; very difficult to do in real life” (Collaborative Friends Debriefing).

February 8, 2017 Class

The professor observed that students enjoyed the interactive nature of this PhET, and he wanted to explore this further while also reinforcing experiential learning of waves interference using the PhET. The professor noted:

I may have deliberately overshot the learning potential because I question: Can you do experiential learning where experiences are preordained? PhETs offer an opportunity to explore, but explore the right element in the right direction, there is a necessary balance, which is a challenge. (Reflection, February 8, 2017)

One way he chose to ground this learning in experience was to connect the phenomenon of waves interference, resonance, and comparison to the Tacoma Narrows Bridge Collapse that occurred November 7, 1940 due to aeroelastic flutter, a Physics concept that the PhET could illuminate. The professor noted in this activity he “allowed students to ‘discover’ standing waves but this came with an issue: in the PhET the string is not fixed at both ends. Thus, because of possibilities and interactivity, it was time consuming for students to search for the harmonic frequencies” (Reflection, February 8, 2017). The professor felt that it would have been better to use the Waves on a String PhET as a pre-learning activity, and then in class use it interactively. The professor observed that some PhETs are “better as an activity than demonstration; some are great to illustrate Physics concepts” (Reflection, February 8, 2017).

The debriefing discussed the pedagogical approaches and opportunities with different PhETs and how they can be used in different ways to construct learning about Physics: illustrative, demonstrative, discovery. PhETs offer an “opportunity to explore the right element in the right direction. Finding a balance is a challenge” (Collaborative Friend Debriefing) as decisions had to be made regarding whether a specific PhET would be used as a pre-learning activity, a scaffolded learning activity, an experiment, and/or an assessment aid.

February 8, 2017 Class—Next PhET

Later, on February 8, 2017, the class used the Circuit Construction PhET to construct simple circuits with batteries, resistors, and switches. Measurements can be done using built-in ammeters and voltmeters. Using the Circuit Construction Kit PhET, as a means to have students construct these devices while in class, the professor noted that while PhETs are not as authentic as a laboratory experiment,

simulations achieve the same goal of allowing students to directly interact with physical concepts without reference to a mathematical description. Through a simulation, students will begin to develop some “physical intuition” for the Physics concept or phenomenon. It is my expectation that this simulation-based physical intuition will help ease the students’ transition into a mathematical description of the underlying physical concept. However, labs are really important. I do not see PhETs as a replacement for labs. Labs are essential in science. The issue for me is when students perceive labs as separate from lecture. (Reflection, February 8, 2017)

Students noted that they valued the use of PhETs to connect their in-class learning with that in their labs. Some of the comments emphasized: “there were lots of calculations you could do in reference to the sim that carry over into the lab” and “PhETs allowed to verify calculations” in “a real-life digital way” (April Student Survey). During the debriefing, it was noted that PhETs offer a bridge between the lecture and the lab: “[Simulations] are like the half-way point between the lecture and lab and students seem to see them this way” (Collaborative Friend Debriefing). One

student noted, “One of our online assignments had a simulation to build a circuit and measure the current. When doing that I realized I was using the wrong formula for one of the questions. So it helped me figure out what I was doing wrong” (April Student Survey). The debriefing about these two PhETs in practice (Waves on a String and Circuit Breaker) highlighted that the latter PhETs’ interactivity represented a discovery in relation to their learning potential as they “Allow students to explore the parameter space freely—PhETs allow freedom to explore” (Collaborative Friend Debriefing).

The research assistants noted how students noticed a point that the professor and critical friend did not consider. In this session, students were working with the Circuit Builder, and the student research assistants observed:

The expert might overlook things that students don’t (e.g., the red wire in the Circuit Builder PhET). Students might focus on the wire whereas the professor likely not. No matter how much the professor tried to put himself in the students’ place in terms of their learning, a question about wire colour would not occur to him. It was a question in relation to building a circuit that the students made, and it was the research assistants who noticed. (Collaborative Friend Debriefing)

The coloured coating on wires is only to make it easier to recognize individual wires in a circuit; the specific colour of the wire has no effect whatsoever on the function of the circuit. This is well known to experts, but not to students.

March 6, 2017 Class

The Physics concepts for this session were waves and motion and used the PhET Wave Interference. The Wave Interference PhET allows students to observe interference and diffraction of water, sound, and light waves. Built-in measuring devices allow quantities such as amplitude, frequency, period, and wavelength to be measured. While the professor indicated this PhET is older and geared to more advanced Physics students (Reflection, March 6, 2017), afterward, the professor noted that this PhET was “effective for its purpose” (Reflection, March 6, 2017), which was to help students visualize the Physics phenomena of wave interference and diffraction. The PhET functioned as demonstrative; students could visualize the Physics concept, an observation also noted by students as a reason they appreciated the PhETs used. Students made comments such as: “The PhET was visual, very visual. I could ‘see’ wave interference” (April Student Survey). During the debriefing the researchers discussed how this PhET is an example of a “Physics concept that is difficult or impossible to achieve in the reality of a lab” (Collaborative Friend Debriefing).

The professor began to think about his PHYS 105 class and consider PhETs as an “Opportunity to ‘show off’ cool things in physics” (Reflection, March 6, 2017) such as using the PhET to

demonstrate Wave Interference. Through collaborative friends meetings, this element was debriefed with the following comments: “This is a classic experiment in Physics. It is an important demonstration for students to see so they can tie Physics back to phenomena.”

During this debriefing, the professor stated he:

Couldn't resist the idea of bringing in beauty of Physics—universality—different manifestation of the same underlying phenomena. I hope it made an impression. I don't want Physics to be a forced march through mathematical equations—Physics is a beautiful subject. (Collaborative Friend Debriefing).

March 22, 2017 Class

The PhET States of Matter demonstrates how molecules can form a solid, liquid, or gas. Through the PhET, students can change the temperature and volume of a substance and watch the phase of the molecule change and observe the state of matter change as a result. The professor noted concerns he had prior to delivering the lesson:

I am using it as a demonstration, so no student interaction. It is a newer PhET, but it is bit more simplistic and perhaps aimed towards younger students. Conceptually its quite useful but pedagogically it is difficult to find a way to bring it into a lesson. (Reflection, March 22, 2017)

The professor acknowledged that he was “shoehorning” (Reflection, March 22, 2017) the PhET into the session because it was “A nice PhET and I wanted to use it; it was too cool to resist” (Collaborative Friend Debriefing). In thinking about this after instruction, the professor realized it was not a strong choice. He noted that he wanted to use the PhETs as a “pseudo lab and if I could not figure out how to do that—I was a bit lost” (Reflection, March 22, 2017).

The debriefing focused on discussion of the dimensions of this PhET and the reflections of the professor that “this PhET was more qualitative—it was a conceptual PhET” which was the impetus for a discussion as to the nature of PhETs. “There seems to be three kinds of PhETs for Physics that were used in this semester, and all used differently. Pseudo lab PhET (easiest to use), Conceptual Mathematical Concept PhET, and Conceptual PhETs for Phenomena” and that “all three work for different pedagogical purposes” (Collaborative Friend Debriefing). “It would have been better to have the time to build this into a nice sequence meaningfully. But, the end of semester was rushed” (Reflection, March 22, 2018). One student “felt some PhETs were used simply for the sake of using a PhET” (April Student Survey). This theme carried over into the next lesson.

March 29, 2017 Class

This class used the PhET Blackbody Spectrum to demonstrate how the blackbody spectrum compares to visible light. The PhET shows that adjusting the temperature to see the wavelength

and intensity of the spectrum changes the colour of the peak and the spectral curve. This was another PhET, which the professor felt was “shoehorned in” (March 27, 2017). This PhET was not well liked by students as evidenced in their April 2017 survey. Students indicated it was their least favourite PhET with comments such as: “harder to understand”; “wasn’t covered in class”; “not very interactive”; “did not have extensions to the learning”; “was too simple”; and “diagrams etc. on the board would have been sufficient” for this learning activity. In thinking about this, the professor realized he “tried to get a PhET in last minute” (Reflection, March 27, 2017). The researchers came up with a term for this PhET experience (calling it the students’ “anti-favourite”) and discussed that this learning moment demonstrates that educators “have to be thoughtful in implementing change” (Collaborative Friend Debriefing) rather than trying to “shoehorn” something in; the pedagogical value must be ascertained and carefully thought out (Collaborative Friend Debriefing).

Implications and Discussion

The professor believes changing his teaching practice to integrate experiential learning (Jarvis, 2012) through PhETs created a dynamic space for students’ learning about Physics. He feels they are very well-designed and powerful tools for teaching Physics in an undergraduate higher education environment, particularly for non-Physics majors who may be feeling some uncertainty or anxiety in relation to Physics. The design of the PhETs prompts the professor for pedagogical approaches to use which is helpful especially for professors who may be accustomed to lecture-based instructional approaches. The research team asserts that there is great learning potential from PhETs and connects this learning value to the ZPD of social constructivism (Vygotsky, 1978). Based on the findings of this study, the PhETs provide an illustrative, demonstrative, and interactive learning experience for undergraduate, non-Physics major students, depending on how the PhET is integrated into the lesson and the Physics concepts that are taught. However, it should be noted that Physics professors, who may or may not have specific qualifications in educational theory and pedagogy, may not be aware of the way learning theories such as social constructivism and ZPD (Vygotsky, 1978) can support the learning potential of simulations or other ways to use experiential teaching methods to teach undergraduate Physics.

Physics describes the real world, which is inherently dynamic. Too often, Physics pedagogy uses static representations, such as whiteboard notations or PowerPoint drawings and slides to depict real-world dynamic processes. This subtle abstraction from dynamic reality to static representation inevitably loses something in the learning experience for students. PhETs can represent the essential dynamic nature of Physics concepts and the learning can develop intuitively (Kubricht et al., 2017; Tallant, 2013). At first glance, it may seem that because PhETs are merely simulations, they are inferior to real-world laboratory experiments; however, this

research team asserts that one of PhETs' strengths is in aiding the intuitive development of mental models of Physics concepts (McKagan et al., 2008) taught in class in a dynamic manner, both the visible Physics concepts and those that are not traditionally visible or possible in the real world (Wieman & Perkins, 2006, pp. 290–291). A further strength in the use of PhETs is that they provide a way for professors, who may or may not be educated in educational theory and practice, to think about different ways to make changes to teaching approaches. Although the professor who engaged in this study was knowledgeable about Physics and PhETs, he was unaware of social constructivism, ZPD, or action research as a research methodology for the Scholarship of Teaching and Learning. This study represented a new way of thinking about teaching Physics in higher education.

In this sense, PhETs are more than a technological aid or resource. It can be argued that PhETs can be the “more capable peer” of the ZPD in Vygotsky's (1978) social constructivist learning theory, in much the same way as Cook (2010) described the role of mobile telephones and Alkahtani (2013) described assistive technologies for students with special needs. PhETs can respond to learners' manipulations of settings to illustrate changes in phenomena. PhETs can be used to make visible Physics concepts that cannot be seen with the naked eye, thereby being the “peer” that edifies students' learning. The researchers suggest the PhET simulations used in this study can be categorized to be illustrative, interactive, and discovery based. The authors further suggest that this categorization represents PhETs' learning potential in the ZPD. As students engage and experiment with PhETs, they are also receiving information and making observations regarding the PhETs and Physics concepts. The learning based on these observations were illustrative (mental models forming that illustrate a Physics concept that may or may not be visible to the naked eye in any other form), interactive (mental models forming based on how the students interact and manipulate the PhET that leads to learning), and discovery (mental models that form from discovering new Physics information based on observations from using the PhET). According to Vygotsky (1978), the ZPD is the conceptual space of learning between what a student knows and can do individually, and that for which the student needs some form of assistance to engage (Verenikina, 2010). In this study, the PhETs were the more capable peer supporting the students in their learning of the Physics concepts through visuals and the interactive nature of the PhETs supporting the development of mental models of Physics (McKagan et al., 2008; Wieman & Perkins, 2006).

This can happen in class, at home, as a pre- or post-learning event, a scaffolded learning experience, a discovery-based learning experience, or if a learner is just interested in discovering more. Higher education professors can capitalize on this knowledge through exploring PhETs, and other simulation-based software for its capacity in the social construction of learning and in the role of technologically enhanced learning in relation to the ZPD. The

researchers recommend further studies, qualitative and quantitative, in relation to the efficacy of PhETs and simulation-based learning programs.

Findings related to the theme of accessibility have implications for Physics teaching practice. First, the ability of a Physics instructor to use innovative teaching tools such as PhETs in class is strongly constrained by classroom infrastructure. Theatre-style lecture halls are poorly suited to group-based activities using PhETs during class time. To support the use of PhETs, classroom infrastructure and design decisions should be deliberately made with PhETs and other educational technologies in mind. Second, the variety of devices available for students to use in the classroom, including laptops, tablets, and smartphones, need to be considered in classroom design and in the design of the PhETs themselves. Some of the PhETs utilize Java and Flash, and correspondingly are unwieldy on devices other than laptops. Fortunately, the PhET group is in the process of updating all existing PhETs to use HTML5 (Perkins, n.d.). PhETs that utilize HTML5 are far superior in that they work flawlessly on any device, including laptops, tablets, and smartphones. When this process is complete, the technological limitations of older PhETs will be completely removed, making their classroom implementation much easier and far more likely to be successful.

Interactive Learning is another theme that arose in the findings, which has implications for Physics teaching practice. Seemingly paradoxical, the greatest weakness of PhETs is also their greatest strength: they are simulations, and as such are only representations of reality. To learn experimental techniques and the scientific method, it is imperative that students directly interact with physics concepts in a real-world laboratory setting. However, it is not always the case that labs are the best place for students to reinforce their understanding of Physics concepts. For instance, insignificant issues such as the colour of wire used in constructing a circuit in a lab can confound students, hindering labs' learning potentials (Finkelstein et al., 2005). The great strength of PhETs is that they are carefully designed to avoid these complications that are unavoidable in the real world, therefore they improve students' learning potential. This aligns with Hensberry et al.'s (2015) findings, but in a university Physics class setting. A related issue is that of in-class demonstrations, which are typically performed by the instructor in a Physics lecture while students passively observe. It is essential that students are made aware the Physics concepts they are learning in the lecture are, in fact, represented in the real world; however, students can directly interact with these concepts by using appropriate PhETs for in-class activities. This experiential learning complements the traditional demonstration and should be used more widely in Physics teaching.

The third emergent theme in the study's findings—student engagement—has implications for Physics teaching practice. Students generally enjoy using PhETs and find their use to be helpful in learning physics; however, this is not the case if PhETs as a pedagogical tool are used without

a clear intention as to the pedagogical approach—a finding that is aligned with adult education principles in relation to experiential education (Jarvis, 2012). While it may be tempting to use a PhET because it is appealing visually, or because it is “cool,” the use of the PhET can be underwhelming for students if the learning intention and pedagogical approach is not carefully considered. During a Collaborative Friend Debriefing in January 4, 2017, prior to the official start of classes, the professor noted that, during the early parts of the data collection stage of this study, he thought of PhETs as being “pseudo-labs” that were best used as such. However, it later became clear to him that this is not the case for all PhETs, and that in fact, there are at least three distinct types of PhETs revealed by this study, each of which is best used in different ways: demonstrative, illustrative, and interactive. Physics educators should be aware of this and carefully consider their pedagogy before utilizing specific PhETs in the classroom. As well, continuity between lecture, lab, and PhET material is crucial. If the connection between the PhET and the Physics concepts it is meant to illustrate is not made clear to students, learning can be compromised. PhETs are powerful tools to support student engagement, if used correctly.

Conclusions

PhETs offer a way for instructors to make Physics concepts dynamic and illustrative. This action research study found that PhETs can act as the more capable peer in Vygotsky’s ZPD due to their powerful design that highlights the relevant core Physics concept and takes away or makes variable the complications of the environment or equipment, something that cannot be done with labs.

This study recognizes labs as essential experiences for Physics students. Experimentation and observation are critical to the scientific method, and labs are where these must be introduced to students. It is therefore crucial that lectures link back to labs. PhETs can be used to bridge the gap between lecture and lab by offering a simulated and therefore idealistic exploration of Physics concepts in a visual and dynamic way. This allows instructors to effectively use PhETs as scaffolds for learners to build mental models of Physics concepts.

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