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Student engagement and learning with PhET interactive simulations

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Summary. — There is considerable evidence that PhET interactive simulations can be powerful tools for achieving student learning of science. Recent research conducted with PhET Interactive simulations has focused on the specific aspects of simulations that help students build a conceptual understanding of the science; specifically the value of showing the invisible, the use of analogy and effective levels of guidance with simulations. Educators have found that use of heavily guided activities does not elicit deep thinking and learning from students; while other studies have found that with pure discovery learning students are not able to "discover" the science for themselves. Recent studies reveal that appropriate scaffolding of the material is needed to help students build a mental framework about concepts. Then students can construct their own understanding within this framework. Our work has focused on understanding how students use simulations to construct this mental framework and the effect levels of guidance have on students' use of simulations. Hundreds of individual student interviews have been conducted during which the students describe what they were thinking as they interact with simulations. Careful analysis reveals that showing the invisible and use of analogy both facilitate students' construction of their understanding; while the nature of guidance influences the amount of student engagement.

PACS 01.50.-i – Educational aids.
PACS 01.50.F- – Audio and visual aids.

1. – Introduction

PhET Interactive Simulations are a substantial ($\sim$ 85) and growing suite of professional quality simulations (sims) for teaching and learning science. The sims are freely distributed from the PhET website `http://PhET.colorado.edu`, with roughly 10 million uses in the past year. The majority of PhET sims are for teaching physics but there are a growing number in chemistry, biology, math and other sciences. Considerable research has investigated the use of PhET sims in a variety of educational settings (PhET Team, 2009). Interactivity in computer simulations is known to be beneficial for learning, (Bodemer, 2004; van der Meij, 2006) but the degree of interactivity can vary greatly for

A train crosses a 100 m bridge at 5 m/s. After crossing the bridge it accelerates at 2 m/s^2 for 10 seconds to reach its normal cruising speed.

1. How long does it take the train to cross the bridge?
   100 m / 5 m/s = 20 seconds
2. Just after crossing the bridge, what is the train's velocity?
   5 m/s
3. What is the train's final velocity?
   $v_f = v_o + at$ = 0 m/s + 2 m/s^2 x 10s = 20
4. What is the train's average velocity from the start of the bridge until it reaches cruising speed?
   $v_{avg} = (v_f - v_o)/t$ "What is **v_f**? I don't see it in the problem!

Fig. 1. – Typical student solution to a physics problem.

different educational simulations. PhET sims provide a high degree of interactivity in terms of user control, dynamic feedback, and multiple representations (Adams, 2008a; Adams, 2008b).

As teachers we've all watched our students work through a problem that they "should" know how to do. After having heard a lecture or two on the material and read the appropriate section in the text book, problems are given such as the example in fig. 1. The student works through each question seemingly without creating a mental representation or making sense of the equation. This can be seen in mistakes such as always putting in zero for the initial velocity. Another common behavior is for students to forget what they have already found. In this typical example, the student finds an equation for question 4 and then gets stuck trying to find the final velocity when they just calculated it in question 3!

Educational researchers have found that with direct instruction students do not engage in their school work as a scientist would (Piaget, 1970). They do not investigate, explore, ask questions, make connections or deduce the rules. Instead they just answer what has been asked, transfer and retain very little. Why is this? One might postulate that students don't know how to be a scientist, or they don't care and are in a hurry and that they are underprepared so not able to do the work.

In response to direct instruction not working, many educators tried pure discovery learning. They'd supply students with a selection of equipment (batteries, light bulbs, magnet, a compass and wire) and tell them to figure out how to accomplish a certain task (figure out how the magnet can affect the light bulb). In activities such as this students are quickly overwhelmed, were confused without directions and have many false starts. Others have devised pure discovery activities that would have students being actively productive (build a paper boat that can hold the most paper clips) however, the students come away not knowing what is important or what they have learned (Mayer, 2004).

This paper will briefly discuss learning theories about how to productively build knowledge and different modes of student engagement. Students explore PhET simulations through *engaged exploration* which is a mode where they are exploring via their own questioning demonstrating scientist-like behavior. A few classroom studies will be briefly described as well as an in depth interview study showing how sensitive this mode of engaged exploration is to the level of guidance that is provided.

2. – Learning theories

Research on learning shows that students need a framework of the main ideas to build knowledge on (Bransford, 2004). In other words learning is an active process where students are active sense makers. Learning is thinking and not just doing. Direct instruction does not help students build their own mental framework while pure discovery might help build a framework but it'd take about 500 years. Successful activities should help the student identify what is important, and build a mental framework for examining the phenomena. Without this framework, there are too many details to for students to follow and remember.

To build a framework students must be actively making sense—sense making mode—rather than simply looking for answers—student mode. For example a student may believe the problem is about doing math as in the example with the train in fig. 1. In this case, the student is plugging numbers into equations and often quickly goes down fruitless paths of calculating numbers—math mode. A rewording of the question could put the student in the sense-making mode where they are expected to think about and discuss what could be going on rather than doing calculations (Dweck, 1999; Bing, 2008).

Thus to help novices construct a suitable mental framework doable tasks/balance challenges that elicit sense-making about the phenomena should be presented. The material needs to be scaffolded so that challenges are balanced and attainable by the typical student. This helps provide motivation since students feel a sense of accomplishment with each little success rather than frustration (Malone, 1981).

Extensive student interviews with the PhET sims have shown that students explore the sims through self-guided engaged exploration only if the interviewer provides minimal to no guidance. One may ask how this is different from pure discovery. We believe there are two aspects. First, the simulation through its structure and appearance provides considerable implicit guidance. The second reason is that the simulation provides balanced challenges. The simulations encourage novices to figure out on their own what types and pieces of information are needed for them to solve the task.

As they progress through the simulation a mental framework is built with connections that include an expert's visualization of the phenomena. This new framework may not be complete; however, due to the existence of a framework, the missing pieces can usually be fit into this new framework with only minor extensions.

3. – Background

The PhET sims are designed with an intuitive interface for students and minimal text (fig. 2). The sims are interactive and animated, responding instantaneously to student interaction. Real world items (*e.g.* Light bulbs, bicycle pump, skate boards) are used so that students see the connections between the phenomena and their existing knowledge. However, sims have the additional benefit of being able to make the invisible visible and provide multiple representations (macroscopic, microscopic, graphs, etc...).

One of the key features of sims is the inclusion of balanced challenges such as little puzzles and clues. These challenges are attainable and slowly bring the student to the main goal of understanding the underlying scientific concept via the exploration of physical phenomena. The students interact with the simulations via engaged exploration

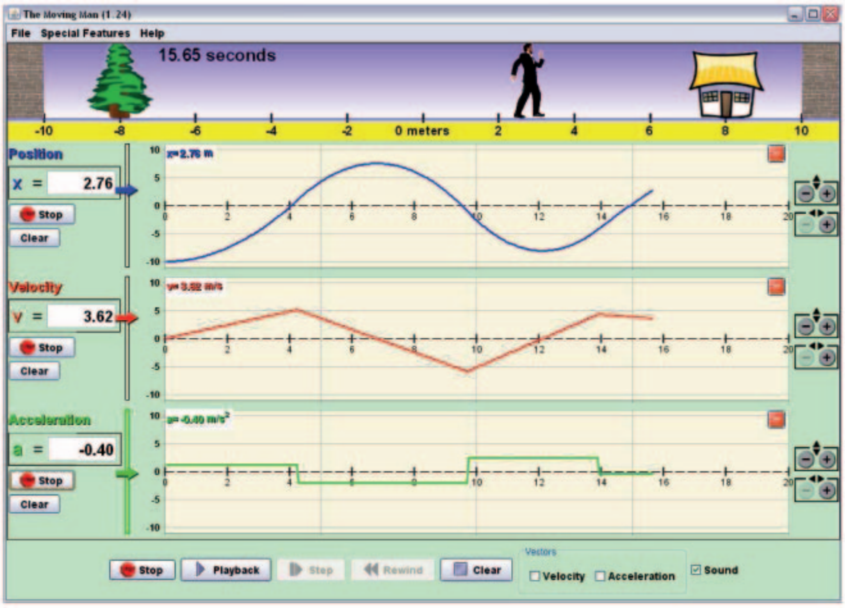

Fig. 2. – Screenshot of the Moving Man. Student's can either drag the man or use the sliders to set the position, velocity or acceleration and watch the man move.

where they can interact with this visual environment at their own pace investigating what they are not sure about and building an expert-like mental framework around the concept as they see what features affect how the simulation behaves. This creates an understanding that includes a visualization of the phenomena and many connections between the bits of knowledge.

As a part of the development of PhET simulations, we've video recorded over 300 think-aloud style interviews with more than 100 different student volunteers. During these interviews, the student is not asked for their opinion or feedback on the simulation, only to think out-loud as they explore. Four to six 30–60 minute interviews are conducted with each version of a simulation. Interview results are used to modify the simulation if necessary and then a new series of interviews are conducted with new students. This process continues until the simulation is eliciting only correct concepts and the interface is intuitive to use.

The PhET simulations are very involved, interactive animated environments that create a unique opportunity for learning not only for the student but the researcher too. The sims create a common visualization and probe into the student's mind which provides many benefits such as when the student becomes quiet during an interview, the researcher can "see" what the student is thinking by watching what they are exploring with the simulation. The simulation also provides a common vocabulary. Students often use words they've gotten from the simulation or the researcher can watch what the student is using when they use a particular term to see more precisely what the student is thinking. If the student does not know what word to use for something, they simply demonstrate it with the simulation.

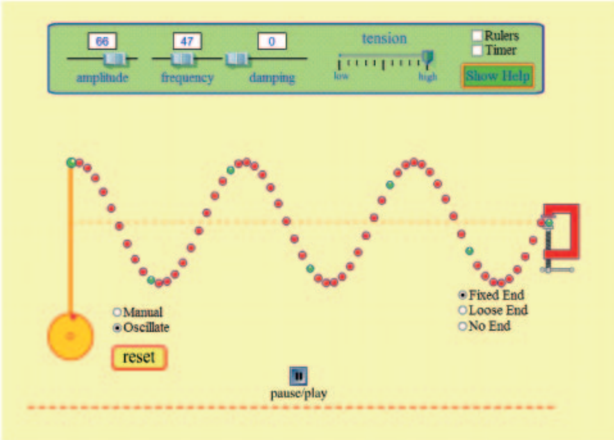

Fig. 3. – Wave on a String simulation. The user can grab the end of the string and oscillate it or use the oscillator to do it for them. Amplitude, frequency, damping, tension and time are all adjustable.

3˙1. *Previous studies.* – In a previous study it was shown that the use of PhET simulations (fig. 3) in lecture can produce much higher results on in class conceptual questions when compared to a demonstration using real equipment. The simulations show physical phenomena using real world objects but allow for time to be slowed and do not include other distracting unnecessary details that typically accompany a demonstration with real equipment (Finkelstein, 2006).

We have engaged in several studies comparing the effectiveness of PhET sims to real laboratory equipment (Finkelstein, 2005). The results of these studies demonstrate that simulations help students' conceptual understanding about the phenomena. For example, one two hour lab of an algebra based physics course was divided into two groups—those that only used a simulation (CCK shown in fig. 4) and those that only used real equipment (bulbs, wires, resistors etc.). The lab activity written around the sim/equipment was identical otherwise. On the final exam (6 weeks later) three questions were asked about DC circuits. The students who had used CCK in lab performed statistically better on average than the students who used real equipment. The averages for the two groups were identical on the exam questions that did not address circuits. In addition, the lab was followed up by an activity where both groups used *real* equipment. Students had to build a complicated circuit and then describe how the circuit would react if they created a break in a specified location. The students who had used the sim for the previous $1\frac{1}{2}$ of lab were faster on average and completing this challenge. This is consistent with their attitude during lab where the sim students explored and investigated without needing much assistance from the Teaching Assistant, while the real equipment students were nervous about breaking the equipment or themselves.

In addition to measuring learning on assessments we document affective differences when using sims compared to other instructional materials. As with CCK in the lab above, where students were more comfortable trying things with the simulations than with real equipment. The introductory quantum mechanics course at Colorado uses the suite of 18 quantum simulations (Mckagan, 2008; McKagan, 2009). Here are two

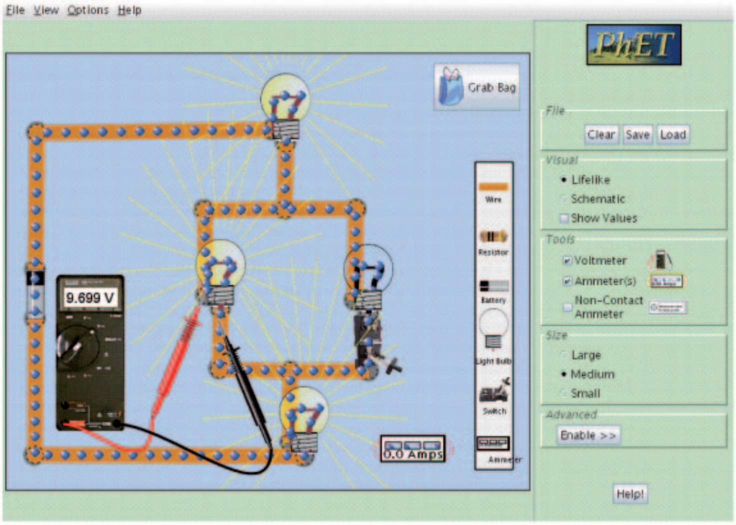

Fig. 4. – The Circuit Construction Kit (CCK). This simulation allows users to build any circuit they can imagine with wires, batteries, resistors, light bulbs and switches. An ammeter and voltmeter are available for taking measurements. When a circuit is completed the electrons move and the light bulbs will light!

representative student comments from that course:

> *"I definitely not only enjoyed the simulations, but I'd go as far to say that the simulations taught me the most about the course because I could really visualize the inner workings of the physics processes that were going on."*

> *"I thought the simulations were great. It helped me to gain intuition about the topic. This is especially useful in quantum mechanics where it is not normally possible to directly observe the described phenomena."*

4. – Learning and engagement

As mentioned above, during interviews we have found that for students to undergo self-guided engaged exploration of the PhET sims only minimal guidance must be provided. Either the students are simply asked to play with the sim or one or two open conceptual questions are asked before they open the sim. A controlled study to explore these findings more carefully using two specific types of interview guidance was performed Open Conceptual Questions and Gentle Guidance. "Open Conceptual Questions" uses one or two challenging conceptual questions to trigger a self-driven exploration, and "Gentle Guidance" uses a carefully-designed activity that asks students to investigate particular controls or features of the simulation. In addition to studying how students interacted differently with the simulation under those two conditions, a third group had two questions omitted from the Gentle Guidance activity to determine if guidance would restrict exploration and affect what students see in the simulation (Adams, 2009; Paulson, 2009). This study used Faraday's Electromagnetic Lab (fig. 5).

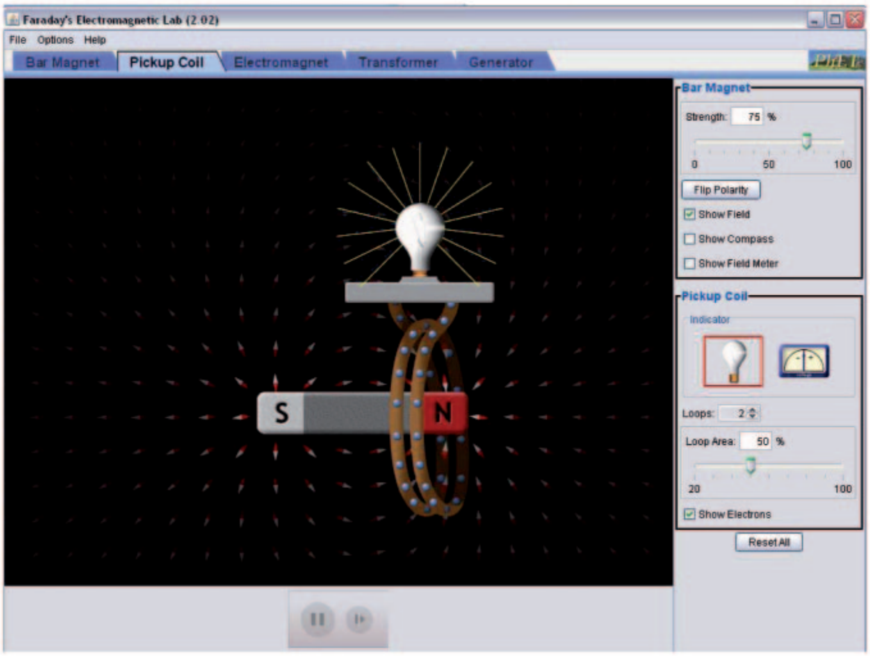

Fig. 5. – Screenshot of Faraday's Electromagnetic Lab. Here the "Pick up Coil" tab is shown when the magnet is moving to the right through the coil. The red and white diamonds represent the magnetic field and the blue spheres represent electrons.

4·1. *Open conceptual questions.* – An interview with open conceptual questions includes questions such as: "Can a magnet affect an electron?" and "What are some ways you can make a magnet?" These questions are asked before the student sees the simulation. The open conceptual questions that work best are open, conceptual questions that do not ask specifically about the simulation, but rather ask about the actual science concept. After answering the questions, students are asked to play with the simulation and think out-loud as they do so.

When students explore a simulation with only these open conceptual questions, we observed them explore many different things, choosing the most inviting items first. During this engaged exploration, students build a mental framework and fill in the information they've identified as important via their own questioning. Typically about half of the interviewees spontaneously revise their answers to the open conceptual questions as they explore, while the other half appear to have forgotten the questions. Again, if the simulation is too complicated or too intimidating, students do not spontaneously explore the simulation.

Interviews using these types of open conceptual questions result in very impressive student learning. As an example we will describe a typical interview with Faraday's Electromagnetic Lab with students with no previous knowledge of the subject. All students work through the various tabs, typically taking just under an hour to do so. All students learn that electrons move only if the magnetic field is changing and that this movement lights the light bulb. If there are more loops of wire or if the area of the loops is larger, the bulb will be brighter. They also discover that a coil of wire attached to a battery has moving electrons that create a magnetic field that behaves exactly as the bar magnet does. Students are then able to successfully adjust all the items necessary to improve the efficiency of a generator (sample transcript can be found at Adams, 2008).

4·2. *Gently guided.* – Gently guided interviews include a series of questions typical in educational activities along the lines of "In the 'Bar Magnet' tab, identify the things on the screen and in the controls in the control panel (at the right.) A. What does the 'Strength' slider do?, B. What does the 'Field Meter' do? etc..." With this sort of activity we see that student exploration is limited to looking just enough into the specific aspect that has been asked about to answer the question. Then they wait for the next question. They rarely explore beyond the bounds of the question. This causes limited mental framework development because students are not asking their own questions. Often students are not able to tie the bits of information that they've learned together into complete ideas.

With this sort of guidance the responses are not as simulation dependent, since the students are not engaged in exploration. The one exception to this is when the simulation is exceptionally engaging—some students will go ahead and explore a bit beyond the particular question. Gently guided activities can be reasonably effective; however, only if very carefully designed through a cyclic process of writing, interviewing and then rewriting the activity until it takes the students to all of the particular aspects of the simulation they need to examine to understand the concept. The amount of learning with this type of gentle guidance is extremely sensitive to question choice, and so can have widely varying results.

Based on these results we hypothesized that by adding and removing particular questions we could direct which aspects of the simulation the students notice. We called this the "Missing Pieces" (MP) treatment. Two questions which mentioned three simulation elements were removed from the gently guided activity. When students were interviewed using this protocol, they did not notice the three items; however nearly all students who had the open conceptual questions (which do not explicitly mention any sim items) did notice these elements (fig. 6).

It is worth noting that interactions with other students while using the simulation can dominate student behavior compared to the effects of instructional guidance with the simulations. When the sim is effective with minimal guidance with an individual and excessive guidance narrows the focus of the use as discussed above, then social activity can compensate for the undesirable limitations caused by excessive guidance. As evidence, we have had reasonable success using guided inquiry style activities in class with students working in groups of two to four. They will explore the simulation somewhat beyond the bounds of the guidance due to questions within the group. (*i.e.* "What happens if you change this?")

5. – Current studies

This coming year we are identifying the characteristics of homework that will take advantage of the unique features of simulations as well as focusing on the effectiveness in the chemistry classroom. We are currently midway through a study that identifies if, where and how showing invisible representations such as current in a wire or a magnetic field helps with student understanding.

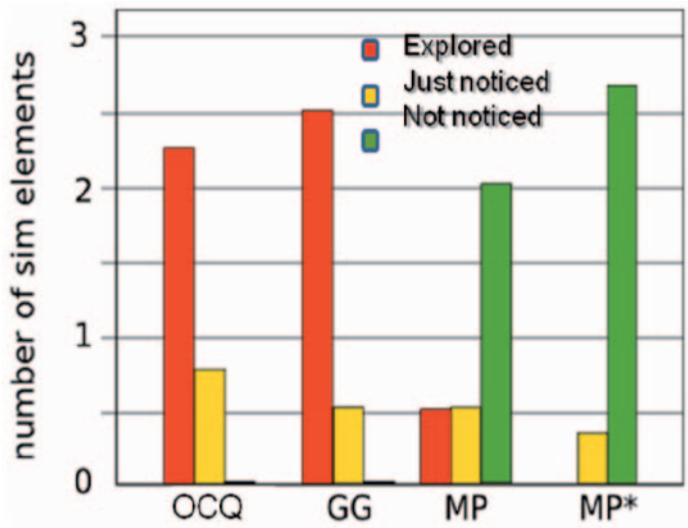

Fig. 6. – Graph shows the average number of the three sim elements that were noticed by each group. Explored means students carefully investigated the element, just noticed means they clicked on it but did not show any further recognition that it existed and not noticed means there was no indication that they saw the element as existing. MP* is the results for the missing pieces group of one anomalous student is removed.

A short description of each study that was completed this past year is included below.

5˙1. *Use of analogy to construct understanding.* – This work is an exploration into furthering our theoretical understanding of how students use the simulations to make sense of the science. We examine student learning with computer simulations along two themes—*engaged exploration* and *generative analogy*. Engaged exploration is a process of learning that involves students actively thinking, sense-making, and, exploring via their own questioning. PhET simulations are designed to support and promote engaged exploration. Analogy, broadly stated, is a cognitive tool that uses familiar ideas to learn about or make sense of an unfamiliar topic. We investigate students' use of analogy in the context of learning from the Wave Interference simulation. We see that the use of analogy to generate new ideas is a key component of student learning with computer simulations. Our findings suggest that, given learning tools that are sufficiently engaging and provide appropriate scaffolding, students make substantial use of analogy in a generative fashion (Podolefsky, 2010a).

5˙2. *Socio-cultural context.* – The PhET computer simulations (sims) have been demonstrated as successful tools for teaching and learning physics. We situate sims in a socio-cultural-historical context. Sims are cultural tools designed to embody certain norms and practices of the physics community, particularly learning through exploration. We focus on interactions between three scales of tools. We find that representations that make up learning materials, the nature of the materials, as well as the environments in which these materials are embedded, all play important roles in how students engage in learning. A series of studies supports our claim, especially insofar as how students perceive the nature of the introductory physics labs. We believe features of sims that support scientific exploration by students may be applicable to other learning materials. In our efforts, we are primarily interested in engaging students in interesting enough activities that they are driven to learn significantly on their own (Podolefsky, 2010b).

5·3. *Choices when learning with sims*. – We examine student choices while using PhET computer simulations (sims) to learn physics content. In interviews, students were given questions from the Force Concept Inventory (FCI) (Hestenes, 1992) and were allowed to choose from 12 computer simulations in order to answer these questions. We investigate students' choices when answering FCI questions with sims. We find that while students' initially choose sims that match problem situations at a surface level, deeper connections may be noticed by students later on. These results inform us on how people may choose education resources when learning on their own (Podolefsky, 2010c).

6. – Conclusion

Teachers are often frustrated that their students do not engage in their school work as a scientist would. They do not investigate, explore, ask questions, make connections or deduce the rules. Instead they just answer what has been asked, transfer and retain very little. Why is this? One might postulate that students don't know how to be a scientist, or they don't care and are in a hurry and that they are underprepared so not able to do the work.

We have seen that with PhET Interactive simulations students do engage in scientist-like exploration and that this results in greater and deeper learning of scientific concepts. Taking the time to explore the simulation via their own questioning, making connections and deducing the rules. Getting students to engage productively with an activity and exhibit scientist-like behavior requires both balanced challenges and eliciting the correct mode of engagement. The PhET simulations have been demonstrated to be successful at both of these tasks during interviews, in lab and during in class activities. Recent studies of PhET simulations reveal that use of analogy (Podolefsky, 2010) facilitates students' construction of their understanding; while the nature of guidance influences the amount of student engagement.

We've found, through extensive simulation interviews, that exploration of the simulations under no guidance or with open conceptual questions promotes students to explore the simulations where they gain physical insight into the phenomena via their own questioning. These results are consistent with research on how people learn. The simulations have implicit guidance and balanced challenges which encourage engaged exploration where students approach problem solving and knowledge acquisition in a similar fashion as experts. Engaged exploration with simulations in the no guidance or open conceptual question condition provides only enough guidance to require students to explore via their own questioning. Students form a mental framework through this process. Through its design (controls, features, visualizations), the simulation can influence this framework, shaping it into one that is similar to an expert's.

* * *

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