

# Computer simulations to classrooms: tools for change

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**Abstract.** This paper situates PhET computer simulations (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: representations, materials, and environments. We examine critical features of tools across these three scales which support student learning through engaged exploration. We support our claims with data from studies of use of sims in introductory physics laboratories.

**Keywords:** Computer simulations, tools, socio-cultural, representations, physics education research

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## INTRODUCTION

Traditionally, introductory physics courses consist of several lectures per week accompanied by a laboratory section. In labs, students generally work with equipment such as circuits, magnets, or gliders while following a set of instructions. The learning goals for such labs can be multifold. Some typical goals are: to have students confirm physical laws through experiment, to give students experience working with laboratory equipment, and/or for students to engage in scientific exploration.<sup>1</sup> Each of these goals carries with it certain assumptions about what it means to learn and do science, particularly in the context of an introductory physics laboratory. While these labs are by their nature quite different from the world of professional scientists, there are many elements which can overlap, and the degree to which students engage in scientist-like practices can depend critically on the learning tools provided.

In this paper, we provide a framework for examining how students' practices can be affected by learning tools, such as laboratory equipment, computer simulations, and supporting materials. We use this framework to identify features of these tools which can support, or conflict with, certain learning goals. Further, we argue that engaging students in scientific exploration may require a substantial rethinking of the standard introductory physics laboratory. We believe computer simulations can provide many of the key elements for engaging students in this sort of activity, if properly implemented. We describe how and why, and provide evidence for these claims from classroom observations and student feedback.

## THREE SCALES OF TOOLS

We use the term *tools* broadly to describe elements of a learning environment at three scales. The smallest scale we consider is that of external representations, such as pictures, graphs, or formulas. The next scale is that of learning materials, such as laboratory equipment, computer simulations, and the supporting materials. The largest scale we consider is that of the classroom environment, which is established historically by the institution and locally by the instructor(s) and, to some degree, the students.

### Representational Scale

External representations are essential to any educational material, and a key learning goal in science is for students to learn and use the representations established by the field.<sup>2</sup> On the path toward expertise, students may have many different interpretations of representations. These may or may not align with the community consensus of experts. For instance, students may interpret a sine wave representation of sound as representing a transverse wave.<sup>3</sup> On the other hand, students may interpret a picture of compressed and rarefied air particles as a longitudinal wave, and subsequently use this idea to reinterpret the sine wave as also representing a longitudinal wave. Thus, at a conceptual level, we can identify representations that tend to support student sense making, and contrast these with representations that can be difficult or misleading if used alone.

We suggest, however, that representations carry more than conceptual meaning. Representations can also cue epistemic frames.<sup>4</sup> That is, students may view the nature of an activity very differently depending on the representations presented. For instance, sine waves and formulas may tend to cue an “answer making” frame, whereby students assume the point of the activity is to come up with the correct answer. On the other hand, pictures of realistic objects may cue a “sense making” frame, whereby students may try to learn by building on their prior knowledge and experiences. Note that realistic objects need not be things such as cars or roller coasters. Representing a sound wave as air particles, or electrons as blue spheres, may also cue sense making. These representations can give students more concrete ways of thinking about the phenomena, and therefore substantially change the way students view learning.

### Materials Scale

Standard labs use equipment accompanied by a set of instructions that guide students through the activity. While from the outside this arrangement may appear to engage students in scientific exploration, we and others<sup>1</sup> suggest that what students are actually doing is vastly different. A key element of acting like a scientist is exploring in a somewhat self-guided fashion, asking questions, formulating ideas, and conducting tests of these ideas. What we have found is that giving students too much guidance may short circuit this learning through exploration.<sup>5</sup>

However, in order for lower levels of guidance to foster exploration, the learning materials provided must sufficiently scaffold this type of activity. We claim that computer simulations, particularly the PhET simulations (sims),<sup>6</sup> provide such scaffolding, whereas standard laboratory equipment may not. This scaffolding includes carefully controlling for what a sim user can (and cannot) do, as well as what the user is (and is not) shown. Both of these depend critically on elements at the representational scale. We may design a sim such that users tend to see more concrete representations first and see the more formal representations only after a substantial amount of interaction with the sim. Sims also allow users to manipulate objects in ways that would be nearly impossible with real equipment, but users are also constrained such that these manipulations tend to provide just what students need to see and little more. This is particularly important in two respects: 1) allowing students to easily manipulate objects and variables provides a low risk entry point to scientific exploration, and 2) constraining what students can do reduces cognitive demands and frees up resources for

sense making and development of an expert-like mental framework.

### Environment Scale

When trying to change the nature of a physics course, representations and materials may be the most apparent components on which to focus. However, changing these is neither simple nor straightforward. In a sense, doing so is to go against long and deeply entrenched historical traditions.<sup>7</sup> Many classrooms in which exploration and collaborative group work is to occur are set up for transmissionist instruction. There is a chalkboard at the front of the room and the desks are tightly packed facing the front. This may indicate to both students and instructors that a certain type of learning is to go on. Even if the instructor tries to do things differently, it may be difficult for students to talk to each other, or for the instructor to sit down and talk with groups. This is why some physics departments have radically restructured their classrooms to support inquiry learning.

Even with classrooms rearranged, the “cookbook” lab remains a staple of physics courses. New tools, such as PhET sims, are often implemented in a similar fashion. This may not be the ideal way of using such tools, and, in fact, is not how they were designed to be used. Nonetheless, students and instructors may take on particular roles, cultural norms, and practices by taking part in traditional schooling. Because these environments have been so structured for so long, it may be difficult to recognize alternatives.

But we need not be fatalistic about the effect of historical traditions. While environment can place constraints on what people perceive as possible actions with a tool, tools can also change the way people act and hence change environmental structures. More accurately, new tools can allow people to act in new and different ways, especially if the new tools capitalize on peoples’ natural curiosities. We believe that many students are inclined to learn by exploring, but in many cases are kept from doing so by the limitations of the available learning tools and environment. PhET sims allow for this type of learning, and can change a classroom environment through student engagement in exploration.

### General Model

We represent a general model for coordinating representations, materials, and environments in Figure 1. We draw on the nested layers used by Finkelstein<sup>8</sup> and Cole,<sup>7</sup> focusing on a smaller scale (their *situation* layer is roughly the equivalent of our environment). Representations may include conceptual cues or epistemic cues, and become part of classroom

materials. Materials could be lab equipment, sims, and/or supporting materials. These allow certain actions and provide constraints. Constraints are productive when they reduce demands on students and free up resources for other cognitive (and social) action. Environment subsumes the other layers, and includes physical classroom structures as well as social norms and practices.

Historical traditions drive the structure of layers, generally from the outside in. For example, traditionally, physics labs take place in a classroom, using wires and bulbs, asking students to apply the formula  $V = IR$ . By placing new and different representations and materials in an environment, we may be able to catalyze structural change from the inside out. A PhET sim that represents current flow explicitly and allows students to quickly build circuits (virtually) may promote a classroom environment where the norm is sense making and collaborative learning. These materials may also provoke instructors to restructure classrooms so as to further promote the type of engagement made possible with sims. We note that sims are not the only tools that can change environments, only that they are a well studied example.

## SUPPORTING DATA

We provide data supporting our claims from two sources: 1) feedback from students comparing laboratory activities with and without sims, and 2) classroom observations of students using sims. These data were gathered in a second semester, algebra-based introductory physics course (N~300).

During the 5<sup>th</sup> week of the course, students completed an activity on current and voltage using the Circuit Construction Kit, a PhET sim that allows users to build and observe electric circuits. The following week, students completed an activity using real equipment (wires, bulbs, and batteries). Students then completed an online survey asking them to compare the sim and real equipment labs in an open response question. These long answer responses were coded into the categories shown in Table 1. *Sim Learning* includes responses where students explicitly stated PhET was beneficial for learning and understanding concepts. *Sim Usage* includes responses where students cited advantages to sims (over real equipment) such as ease of use, always working as expected, being able to see useful representations, and feeling like the sims allowed for lower risk experimentation. *Preferred Real* includes students who explicitly stated they preferred the real equipment over sims (usually because they believed they learned more from being “hands on”). *Both* indicates students who cited advantages to both sims and real equipment, and

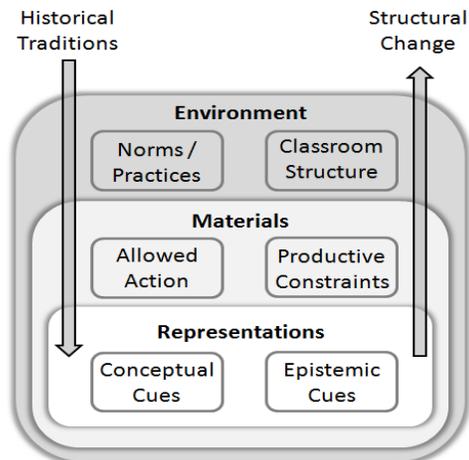


FIGURE 1. General model for scales of tools.

had a preference for using both. Students were often coded into multiple categories.

In these open response questions, a majority of students stated that CCK had advantages for usage, while a small fraction stated an explicit preference for real equipment. While most responses focused on usage, some students explicitly stated that the sims were better for conceptual learning than the real equipment, and a surprising number made fairly articulate statements about the advantages of both.

TABLE 1. Student coding of survey results.

Code	Fraction of Students
Sim Learning	26%
Sim Usage	64%
Preferred Real	22%
Both	42%

A number of students commented specifically on how the sim allowed them to engage in activity that they did not feel comfortable doing with real equipment. Two such quotes follow:

*“The simulation was much more helpful. The reason I found it more helpful is because it allowed me to build different circuits easily while also being able to visualize the current itself. It helped so much that I used the simulation to study for the test. The real life circuit building was ok; it was a bit confusing and not quite as helpful.”*

*“I thought the PhET lab was much more beneficial than the actual hands on lab because the PhET lab drastically reduced the possibilities of something going wrong like the batteries being drained or the resistors not working properly like in the hands on lab. Working with the PhET simulations showed me how circuits should work when everything is working correctly meaning with all other factors controlled.”*

In two follow-up studies, we implemented PhET sims and real equipment into a single lab activity. In the first study, students completed an activity on magnetism, first using a sim on magnets and magnetic fields, then using real magnets, compasses, and electromagnets. The supporting materials already existed for the real equipment, and we made very minimal additions to have students use the sim in the first part of the activity. What we found was that students made limited use of the sim, usually 5-10 minutes, before continuing with the lab as originally written. Observations revealed very little student interaction with the sim other than to answer the questions specifically posed in the lab. Follow up survey data also indicated students did not find the sim very engaging. However, students did point out in this survey that the real equipment was often faulty and stated that an advantage of the sims is that they always work as expected.

We note that the sim used in this study has successfully engaged students in learning by exploring in interviews\*. Therefore, we do not believe that the sim itself is not engaging. Rather, we believe the reason for lack of student engagement with the sim is substantially due to environmental factors and limitations of the supporting materials to drive student exploration. The students were accustomed to cookbook labs, the remainder of the lab was competing for students' time, and we had made minimal changes made to the original lab. According to the model described above, we view this as one example of the historical tradition of cookbook style labs driving an environment that tends to support students following directions (i.e., answer making) rather than taking charge of their own learning.

In the second study, we implemented sims and real equipment in a lab on wave interference. This time, we rewrote significant portions of the original supporting materials, focusing particularly on open ended questions meant to drive student exploration with the sim. Unlike the prior study, we now found that students spent a significant portion of the lab with the sim, usually 30-40 minutes of a 2 hour lab. Observations also revealed that students' conversations with each other and the lab instructor deviated somewhat from the lab as written. Students spent considerable time exploring the sim, asking questions, and trying to make sense of the visual representations of wave interference. In a follow up survey, students pointed out many of the same ideas as in prior surveys about sims, but also stated that use of the sim prepared them well for using the real equipment in the second part of the lab (in this case, a laser and set of double slits).

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\* In this lab, students only needed the first two tabs of a five tab sim.

## CONCLUSION

We have proposed a model of incorporating learning tools, particularly computer simulations, into classrooms focusing on three scales. We find that representations that make up learning materials, the nature of these 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 claims, especially insofar as how students perceive the nature of the introductory physics labs. In the first of two follow-up studies, materials did not sufficiently integrate across environmental and representational scales. In the second follow-up, materials were modified significantly to integrate across scales, resulting in notable changes to students' engagement in the activities.

We do not suggest that computer simulations can or should replace real laboratory equipment. Rather, we believe features of sims that support scientific exploration by students may be applicable to the design of other learning materials. In our efforts, we are primarily focused on engaging students in interesting enough activities that they are driven to explore and learn significantly on their own.

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