Preservice Teachers' Theory Development in Physical and Simulated Environments

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Received 9 June 2004; Accepted 23 June 2005

Abstract: We report a study of three prospective secondary science teachers' development of theories-in-action as they worked together in a group to explore collisions using both physical manipulatives and a computer simulation (Interactive Physics). Analysis of their investigations using an existing theoretical framework indicates that, as the group moved from physical experiments to the computer simulation, their attention shifted from planning their experiments to processing system feedback, which impeded the iterative refinement of their theories-in-action. The nature of the theories they developed also changed. Learners' attitudes toward science and prior experiences affected the exploration process in both environments. In particular, prior instruction in physics and an authoritarian view of science seemed to impede engagement in the development and testing of theories-in-action. Certain features of the computer system itself also impeded exploration. © 2006 Wiley Periodicals, Inc. J Res Sci Teach 43: 907–937, 2006

One of the goals of science education at the secondary level is that our students will ''actually use the cognitive and manipulative skills associated with the formulation of scientific explanations'' (National Research Council, 1996, p. 173). That is, we want our students to observe phenomena, formulate ideas that might explain what they see, and implement strategies to test whether these ideas are correct and over what range of parameters they hold true. In an ideal situation, students will formulate ideas that align with the explanations that have been developed by the larger community of scientists, but significant forces work against this possibility.

First, it is unlikely that students working without guidance or prior knowledge will formulate ''ontological entities [and] organizing concepts'' (Driver, Asoko, Leach, Mortimer, & Scott, 1994, p. 6) that are as sophisticated and productive as those generally accepted by the discipline, the latter having been developed through years of evaluation by a dedicated community of scholars toward a general consensus. A case in point is the kinetic energy construct—that the energy

Contract grant sponsor: National Science Foundation Collaboratives for Excellence in Teacher Preparation; Contract grant number: DUE-9953187.
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DOI 10.1002/tea.20124
Published online 9 May 2006 in Wiley InterScience (www.interscience.wiley.com).

inherent in an object's motion is characterized by half its mass times its velocity squared. It is hard to imagine students discovering this idea for themselves. In fact, Roth, McRobbie, Lucas, & Boutonné (1997) argued that, in cases like this, ''the very principles to be exhibited are prerequisite to seeing the phenomenon'' (p. 110) that we wish them to see. Thus, the role of the instructor as a mediator of scientific knowledge for students is critical (Driver et al., 1994).

A second major constraint is imposed by the limitations of the laboratory environment. The affordances of the experimental apparatus available to students and the experimental skills of the students themselves are often insufficient to make the observations and measurements necessary to develop, or even confirm, accepted scientific conceptions (Roth et al., 1997; Woolnough, 2000). For example, even if students were familiar with the kinetic energy construct, it would be nearly impossible for them to recognize that the kinetic energy of a toy car does not simply vanish when the car hits another object and stops, but is instead converted to other forms of energy. The apparatus and expertise necessary to make that determination are beyond even the most sophisticated of teaching laboratories. This is particularly true in studies of motion (kinematics), where confounding effects such as friction abound.

Computer simulation environments have the potential to address both these issues. Simulation software can provide scaffolding in the form of access to domain knowledge (de Jong & van Joolingen, 1998; Land & Hannafin, 1997), serve as a focal point for discussion between instructors and students (Roth, 1995), and provide a space in which to coordinate concrete representations of abstract ideas together with physical phenomena (Land & Hannafin, 1996; Roth, Woszczyna, & Smith, 1996). Constructs such as kinetic energy or momentum, which cannot be directly observed, can be represented on a computer screen paired with a representation of the physical phenomenon under study; for example, two objects undergoing a collision.

Furthermore, simulation environments can permit users to vary parameters, obtain measurements, and display results much more quickly, easily, and accurately than they could in physical experiments. In virtual experiments, students can isolate confounding effects, such as friction, turning them on or off at will. Thus, simulation environments offer the possibility that students will be able to test hypotheses more deliberately and systematically, and also reach more robust conclusions, particularly for complicated phenomena in which many different effects come into play.

Simulation environments have, in fact, been shown to promote student mastery of standard conceptions regarding forces (Gorsky & Finegold, 1992) and friction (Steinberg, 2000), particularly when students are allowed to test their own conceptions in the simulation environment. Less success has been reported in using simulations for open-ended discovery learning, in which students are expected to develop ideas for themselves from observations. In a very early study with a computer simulation, Boblick (1972) made the claim that students were able to discover that total momentum is conserved (remains constant) in a collision, but the students had already been introduced to the momentum construct itself, the simulation was limited to cases in which kinetic energy was also conserved, and the exploration process was highly scaffolded. In work with a more sophisticated simulation tool, Interactive Physics (MSC Software, 2000), students without these restrictions and scaffolding did not necessarily generate and test the hypothesis that momentum is conserved, but did generate other equally valid, but less general, rules about what happens in collisions (Marshall, 2002).

In general, however, students may not have the requisite experience to use the simulation environment for productive self-directed exploration; such students require ''externally-directed methods for learning'' and are ''unlikely to capitalize on the features of the system'' (Land & Hannafin, 1997, p. 70). Roth (1995) emphasized that students' interactions with a teacher, rather than students' interaction with the software itself, promoted student learning in his study of students exploring motion with Interactive Physics. Further, misinterpretation of the system operation and feedback can actually impede students' exploration. Confusion about the meaning of input parameters in Interactive Physics limited students' ability to generalize rules that they developed using this tool (Marshall, 2002). In work that used the same software package, Roth et al. (1996) also found that lack of a common-sense understanding of how to use the system led students to construct unintended meanings. A lack of familiarity with the software "prevented students from testing specific ideas and models, because they could not implement them in the microworld" (p. 1006).

In fact, an extensive review of discovery learning with computer simulations by de Jong & van Joolingen (1998) found no clear-cut evidence in favor of discovery learning using computer simulations. They reported that the best practices for implementing scientific discovery learning in simulation environments, and when and how simulations might provide benefits beyond what can be achieved in physical experiments, are not yet known, and they called for further study toward the goal of developing a design theory for instructional simulations.

Thus, there is a need to investigate in more detail how the affordances of the exploration environment, whether physical or simulated, interact with the process of discovery learning itself. To that end, we studied three prospective teachers, working together in a group, as they used both Interactive Physics and physical manipulatives to explore what happens to the momentum of objects in collisions. We believe that it is particularly important to understand how future teachers are able to interpret and take advantage of simulation environments. Their facility with such environments is likely to affect their instructional decisions in their own classrooms, as well as their ability to facilitate exploration with computer simulations for their students. Specifically, this research sought to address three questions:

(1) Are there differences in the actions of prospective secondary science teachers as they employ physical experimentation versus computer simulation to investigate, collaboratively, physical phenomena?
(2) How do the affordances of the simulation environment interact with the development and evaluation of theories-in-action in a physical science context? Does this interaction have implications for the design of open-ended learning environments?
(3) How does the learner context (prior experiences and beliefs) interact with prospective secondary science teachers' development and evaluation of theories-in-action? Does this interaction have implications for the design of open-ended learning environments?

Analysis Framework

We analyzed the prospective teachers' exploration of collisions using the model of the development of "theories-in-action" in open-ended learning environments presented by Land and Hannafin (1996). Theories-in-action, as originally proposed by Karmiloff-Smith and Inhelder (1975), are learners' "implicit ideas or changing modes of representation [of the physical phenomena they are observing]" (p. 196). These theories are inherently fluid, generated and modified based on successive observations. Such theories, once developed, may lead the learner to make inaccurate explanations or predictions, even in cases in which the learner has previously demonstrated competence. On the other hand, the establishment of a theory, however unproductive or limited, provides a framework in which counterexamples can be evaluated, a necessary step in the development of a more generally applicable principle. Thus, the construction of scientifically inaccurate or over-generalized theories can be a productive process, as long as it provides the impetus for continued exploration.

The Land and Hannafin (1996) model presents the process of exploration as a feedback cycle that allows for the gradual refinement of theories-in-action. Figure 1 is a representation of Figure 1

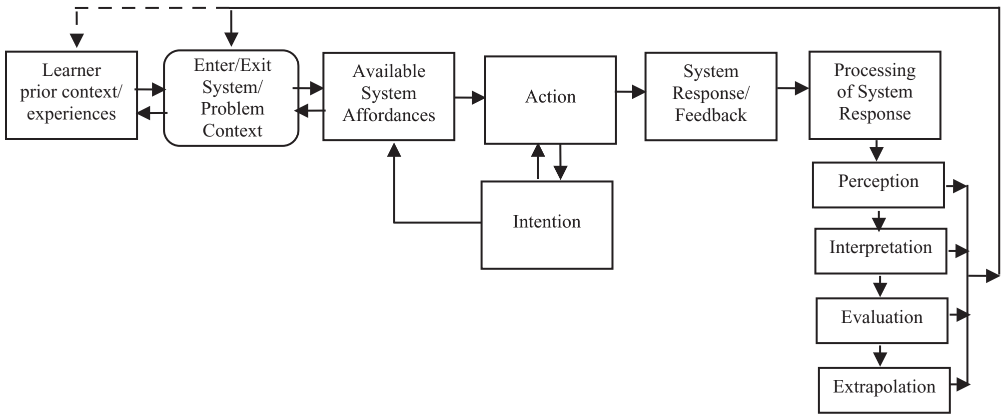

Figure 1. Schematic diagram of the framework used to analyze the development of theories-in-action. Taken from Figure 1 of Land and Hannafin (1996).

from the Land and Hannafin (1996) study. The cycle begins with *learner context* (knowledge, experiences, beliefs). Based on their prior context, learners engage the *problem context* (assigned task or instructions as they interpret it), via the *system affordances* (the open-ended learning environment). They then use the available affordances (design features) of the system to take some sort of *action*, which may or may not involve deliberate planning (*intention*). The system then provides *feedback*, which then undergoes *processing* by the learners. This might lead to another iteration of the cycle, as shown by the arrows leading back to the *problem context* in Figure 1. At this point the *learner context* may or may not have changed, as indicated by the dashed line. With the *learner context* possibly reconstituted by means of the previous cycle, learners once again engage the system context to start the cycle over again. With additional cycles the theory-in-action ‘‘evolves based on progressively refined interactions in the [system]’’ (Land & Hannafin, 1996, p. 39) toward the development of a more productive and generally applicable unifying principle.

In the case of collisions between objects, the generally applicable unifying principles that have been developed by the scientific community are the conservation of momentum and the conservation of energy in isolated systems. A complete understanding of the construct of conservation of momentum includes the recognition that: (1) the vector sum of the momenta of the objects before the collision must equal the vector sum of their momenta afterwards (as long as the objects are isolated from other interactions), but also that (2) the total momentum can be distributed in infinitely many ways among the objects after the collision to satisfy this condition. Likewise, although the total energy before the collision will equal the total afterwards (again, in the case of an isolated interaction), the energy may be distributed in different ways between the objects and in different forms. It is knowledge of how the energy is distributed after the collision, in particular how much remains in the form of kinetic energy, that allows us to constrain the form which conservation of momentum will take and make predictions about the outcomes of collisions.

Methodology

Setting

The study took place in a course in the professional development sequence for the secondary math and science teacher preparation program at a large research university in the USA. The authors were instructors for the course and one of the course objectives was to engage students in reflection about classroom interactions, in particular with regard to content and technology issues. This study focused on one in-class, small-group activity that was part of the regular course curriculum: an exploration of what happens in collisions, using both physical manipulatives and the Interactive Physics computer simulation. During the class period following the exploration, each group reported its results. Students were then given a homework assignment to view a videotape of a high school class performing the same activity and to write a reflection on their own experiences as well as those of the high school students, focusing on the effect of both the technology and the group interaction on the explorations. Finally, in a subsequent class period, students were given a posttest. It consisted of one problem asking them to predict the outcome of a collision between two hockey pucks, given their masses and initial velocities. Because concept mastery was not the objective of the activity, the posttest was not designed as a thorough assessment of student learning with regard to collisions, but rather as an opportunity to see whether students would apply theories that they had developed (or confirmed) in the activity to address the question.

The Exploration Activity

The exploration activity began with a whole-class discussion about collisions. Students identified the possibilities that objects might bounce off each other (elastic collision) or stick together (inelastic collision). They also identified speed, direction, the masses of the colliding objects, and what they were made of as important factors in determining the outcome of a collision. The class discussed the construct of momentum and identified an object's momentum as the product of its mass and its (vector) velocity.

We then tasked the class with working in small groups, using physical manipulatives and then Interactive Physics, to: "Investigate what happens to the momentum of objects when they collide. Are there general rules that apply? Does the mass or incoming velocity of the objects affect the outcome?" The physical manipulatives were hockey pucks to be slid on a waxed lab table or floor. We had added Velcro to the sides of some of the pucks so that they might stick together when they collided. This allowed the students to vary the elasticity (coefficient of restitution) of the collisions. (The elasticity is defined here as the ratio of the difference in velocities after the collision to the difference in velocities beforehand. It determines the extent to which the kinetic energy of the system is conserved.) We also attached Velcro to the tops of some of the pucks so that they could be joined in stacks of two or three, effectively creating objects with two and three times the mass of a single puck. We gave the class access to computers with Interactive Physics, a brief tutorial on the operation of the program, and a data sheet on which to record the input parameters and results of the various experiments they performed.

The exploration (including the whole-class discussion) comprised one 75-minute class period (although more time would have been made available in the next class period had the students not been ready to report results). The group we studied spent more than twice as much time on the computer as on the physical manipulatives. This 75-minute time span was deemed acceptable as students in the course were expected to have already completed at least some formal instruction in physical science, and the activity was not designed primarily with the objective of enhancing content knowledge in this area. We did not necessarily expect the prospective teachers in the class to discover the concepts of conservation of momentum and energy in this short time span, but rather that they would have an opportunity to reflect on the benefits and limitations of the simulation toward the end of employing such technology in a more deliberate way in their own classrooms. We reiterate, however, that previous studies have reported that high school students were able to discover conservation of momentum within one 55-minute class period using a more primitive simulation (Boblick, 1972). Furthermore, 75 minutes is more time than is allotted to exploration of this topic in the prescribed local high school curriculum. Thus, an additional objective for our students was to reflect on what could be accomplished using a simulation during this time period. From the research standpoint, our investigation focused on the process as opposed to the outcome of the explorations, and therefore it was not critical that the participants achieve a particular content objective.

Sample

For the exploration activity, students worked in self-selected groups of three. In each group, one student was designated the ''experiment designer,'' who would decide what experiments to perform; another was the ''operator,'' who would actually carry out the experiments, interfacing with the equipment; and a third, the ''recorder,'' would document the outcomes. These roles were rotated at intervals during the activity.

This study focused on three prospective teachers who worked together as one group. In order to illuminate the details of the investigation, and consequent theory development, it was necessary to record the entire process continuously. Resource limitations prohibited the possibility of recording more than one group. The group was a sample of convenience, selected at random given the restrictions on filming in the class (not all students had given permission for us to video-tape them). A limitation, of course, is that this group might not be representative, but there is no reason to expect that they are not typical of students seeking certification in composite science teaching in our program.

All three were science majors, as are essentially all science teaching candidates in our program. Laura was a post-baccalaureate student with a double major in physics and electrical engineering. Hal, a biology major, was an older student who was looking to teaching as a second career after serving as a technician in science-related industry. In the opening discussion for the activity, he had explicitly stated that all he remembered about momentum (from a prior physics class) was that it was ''conserved.'' Susan was a sophomore, majoring in anthropology. She had completed a physics course the summer before and was currently in her last required physics course. All names are pseudonyms.

Data Collection and Analysis

We video-taped the entire whole-class discussion related to the activity, as well as the target group of three students as they worked together. We then transcribed the video-tape and analyzed the dialog using the model of the development of theories-in-action just described. Following Land and Hannafin (1997), we coded statements as indicative of an *action* or an *intention* on the speaker's part, *processing of feedback* or information by the speaker, or neither. We also coded statements as being indicative of use of *system affordances* (designed features of the software or the physical manipulatives) and/or of the effect of *learner context* (prior experiences, attitudes, beliefs) on the process of developing and evaluating theories-in-action. The authors coded the entire transcript independently, resulting in 89% agreement on the combination of codes assigned to each line. An independent researcher analyzed a subset of the transcript, resulting in approximately the same level of agreement. We then discussed all entries on which there was disagreement and reviewed the original video-tape until reaching a consensus about the designation for each line. We then identified episodes of theory development and evaluated them against the model.

Results of Theory Development With Physical Manipulatives

Cycles 1–8: "Exchange" Theory

The group we studied begins its exploration using the physical manipulatives with Hal in the role of experiment designer, Laura as the operator, and Susan as the recorder. An extremely resilient theory-in-action, which will ultimately become "objects in a collision exchange momenta with each other," begins to develop immediately with the very first cycle of exploration (the entire sequence of cycles is detailed in Table 1.):

Hal: Ah boy. What happens to the momentum when two objects collide. Well . . .
Susan: Are we doing sticky ones or . . .?
Hal: I would say . . .
Susan: Just non-sticky ones? Let's do non-sticky ones.
Laura: Non-sticky ones? Okay?
Hal: Yeah, non-sticky ones first. Yes, I could use all the help as designer as possible. That's my first declaration as designer. Okay, well . . .
Susan: That's our first big scientific word: "non-sticky."
Laura: Okay, we're gonna start with elastic collisions.
Hal: There we go . . . elastic collisions.
Susan: Let's do elastic collisions. This isn't really fair, cuz like, you're a physics major. . .
Laura: I'm just gonna play with the stuff.

In this exchange, the first stages of the Land and Hannafin model are clearly in evidence as the group engages with the *problem context* (What happens to the momentum when two objects collide?) within the *system affordances* of the physical manipulatives, that is, "sticky" and "non-sticky" pucks. Figure 2 shows how the first cycle of theory development unfolds. The *system affordances* clearly interact with the group's *intention* (planning for action). The group's decision is not based on a rationale that energy considerations are important to test, but rather on the kinds of pucks that are available to them. The interaction between the *learner context*, the *system affordances*, and their experimental planning (*intention*) is also evident in that Hal, with the least and most distant training in physics, immediately declares that he needs all the help he can get in designing experiments. He is comfortable with his status as a learner (novice). Susan exhibits her belief that Laura, as a physics major, will have little to learn, and Laura echoes this sentiment, saying that she is just going to "play." The group also indicates that they value "scientific" vocabulary over their own expressions.

As documented in the transcript segment that follows, Laura proceeds by sliding one hockey puck into another (stationary) one, moving to the *action* stage of the development cycle. The hockey puck system provides an immediate, visual *system response* in that the incident puck comes to an abrupt stop, and the other continues with what appears to be the same velocity that the incident puck had prior to the collision. Hal and Susan engage in *processing* this *system response* by noting that the puck that was moving initially comes to an apparently instantaneous stop as a result of the collision:

Hal: Okay. She attempted one moving, one's uh fixed, and uh, she slid, slid the, slid one into the other, and uh . . .
Susan: The velocity one, it stopped when it collided?
Hal: In this case, it pretty much did, yeah.

Table 1
Experimental parameters, outcomes, and theories generated or tested for the 15 cycles of theory development that the group enacted with the physical manipulatives

Cycle	Object 1	Object 2	Elasticity	Outcome	Theory Generated or Tested
1	1 moving	1 stationary	~1	#1 stopped, #2 moving	After the collision, one stops (beginning of Exchange)
2	2 moving	1 stationary	~1	Both objects moving afterward	Test of "one stops"
3	2 moving	1 stationary	~1	Both objects moving afterward	Repeat of Cycle 2
4	1 moving	1 stationary	~1	#1 stopped, #2 moving	Repeat of Cycle 1
5	1 moving	1 moving, same speed, opposite direction	~1	They both recoil at about the same speed, opposite direction	One stops
6	1 moving	1 moving, same speed opposite direction	~1	They both recoil at about the same speed, opposite direction	One will stop only if one was at rest initially
7	1 moving	1 stationary	~1	#1 stopped, #2 moving	Exchange
8	1 moving	1 moving, lower speed opposite direction	~1	#1 recoils with lower speed, #2 recoils with higher speed	Exchange
9	1 moving	1 stationary, glancing collision	0	They stick together and spin around	Sticky means spin
10	1 moving	1 stationary, low velocity, dead-on collision	0	They stick and quickly come to a stop	Sticky means spin (fails)
11	1 moving	1 stationary, glancing collision	~1	Both pucks rotate slightly	A glancing collision means spin
12	1 moving	2 stationary	~1	#1 appears to stop, #2 continues with speed < incident speed	Appears to confirm exchange
13	2 moving	1 stationary, glancing	~1	Both objects moving afterward	Exchange (fails)
14	2 moving	1 stationary, glancing	~1	Both objects moving afterward	Exchange (fails)
15	2 moving	1 stationary, dead on	~1	Both objects moving afterward	Exchange (fails)

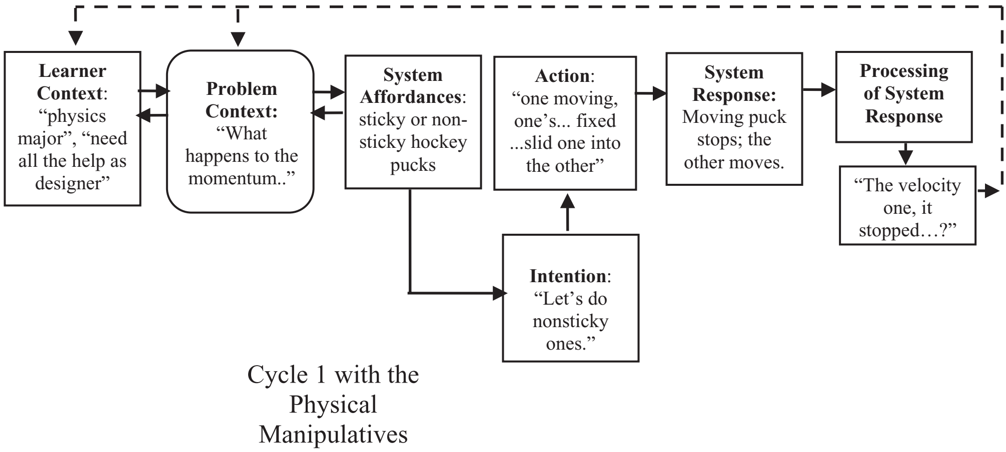

Figure 2. Cycle 1 of the development of theories-in-action. The available system affordances of the hockey pucks (the fact that some have Velcro on the sides and will stick together) drives the group's intentions. The dashed lines pointing back to the learner and problem contexts indicate that Cycle 1 continues into Cycle 2, which is not shown in this diagram.

In this first cycle, the *processing of system response* does not extend beyond *perception*; that is, the group makes no attempt at *interpretation*. Out of this simple observation, however, the extremely robust "exchange" theory begins to develop. At this point, the theory-in-action is simply that "one of the objects will stop as a result of the collision." With no further discussion, Cycle 1 feeds immediately into the learner and problem contexts of a new cycle, which is not shown, as indicated by the dashed lines in Figure 2.

Figure 3 shows the progression to Cycles 2 and 3. Susan, the recorder, asks, "We're still doing non-sticky ones, right?" Laura says yes, and with no further discussion of *intention* moves immediately to the *action* in Cycle 2. Again, the *system affordances* appear to drive her actions. She chooses the other available option with the non-sticky pucks, the possibility of creating a stack of two pucks. She slides the stack of two pucks into a single stationary one and both pucks respond by moving off in the direction of the incident puck, at small, opposing angles from the original trajectory. This time, the group engages in additional *processing of system response*, giving an *evaluation* of the response as anomalous, and leading immediately into Cycle 3, which includes a repeat of the experiment in Cycle 2, as shown in the following transcript:

Laura: Whoa, that wasn't supposed to happen.
Susan: So, more mass and they reflect?
Laura: That just means that I hit it off-center. You can write that down though. One more time then . . . [She repeats the experiment.]
Susan: They still reflected.
Laura: These are farther apart.
Hal: So both of them seem to keep moving in that case. With the moving one with twice the mass, a greater mass, and approximately the same velocity [as the incident puck in the first experiment]. They both moved. Is that significant do you think? Do we need to try, the two [one incident and one stationary], the two going again, just to make sure the one stops, the one that was moving stops and the other one . . . the one continues to move?

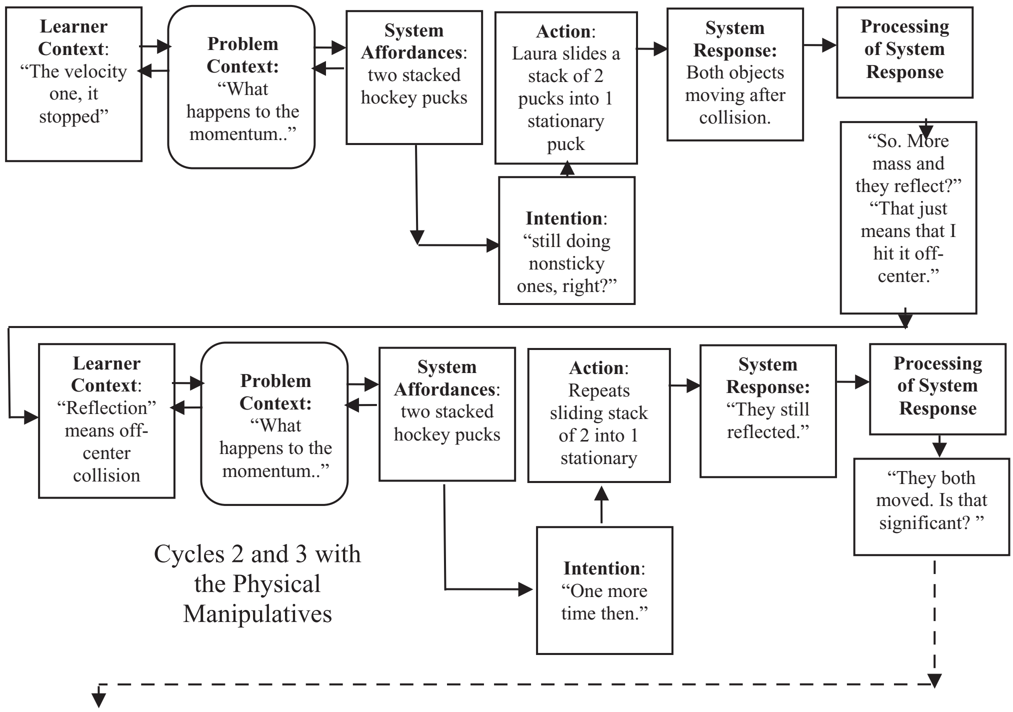

Figure 3. Cycles 2 and 3 of theory development. In Cycle 2, processing of system response extends beyond perception to interpretation. Cycle 2 feeds into Cycle 3, where processing extends to evaluation. Cycle 3 then continues on into Cycle 4, which is not shown, as indicated by the dashed arrow.

Hal's statement that ''both of them seemed to keep moving *in that case*'' (italics added) clearly references the previous case and its resultant theory-in-action, that one of the objects will stop as a result of the collision. Note that, at this point, Hal shifts from a focus on the original goal, to find out what happens to the momentum in collisions, toward an evaluation of the theory-in-action; that is, to test whether ''one will stop.'' Karmiloff-Smith and Inhelder (1975) referred to this as a shift from *action response* to *theory response*, a key element in theory development. Hal's *evaluation* of the *system response* (''They both moved . . .'') leads to the *intention* (''Do we need to try . . .'') of the next cycle (Cycle 4, not shown), as indicated by the dashed line in Figure 3.

In Cycle 4 they repeat the experiment in Cycle 1 and confirm that, when a single puck hits a single, stationary puck, the first one comes to a stop and the second one continues. Hal, therefore, simply concludes that the result with the two stack (that both were moving afterwards) must have been because that collision was ''off-center,'' and with no more discussion the ''one-stops'' theory remains intact.

Next, the group continued with ''a . . .'catalogue' of the different actions'' (Karmiloff-Smith & Inhelder, 1975, p. 201) that are possible with the system. Susan suggests that they try colliding two moving, single pucks into each other head on (*intention*). When Laura collides the two pucks together symmetrically (*action*), they recoil in opposite directions (*system response*):

Susan: Is that what it's supposed to do?
Hal: Okay, they both moved about the same distance.
Susan: I can't remember my physics lab.
Hal: They both moved about the same distance. Now why didn't one st–
Susan: So they reflected equal distances with equal velocity?

The *system response* is clearly in violation of the theory-in-action. In *processing* this response, Hal indicates that he recognizes the contradiction with his question, ''Now why didn't one st[op]?'' Here he follows a pattern of over-generalization, expecting one of the two symmetrically approaching pucks to stop, based on the theory-in-action he has developed. This is despite the fact that, had he considered the symmetric velocity case before the ''one will stop'' theory was established, he probably would not have expected one of the pucks to stop. More than likely he would have predicted that they would bounce back from each other, as they did. The idea of one puck stopping in the symmetric case is, in fact, so counterintuitive as to beg the question of *which* puck Hal expected to stop.

Susan's *prior context* clearly influences the way she processes the *system response* here. In questioning whether the pucks should have recoiled, she cites her physics lab as a source of authority—that is, what happened in the physics lab is what is ''supposed to happen''—in contrast to her own observations of what actually did happen. In this case, however, she cannot remember the canonical outcome. Her *processing* of the response (''So they reflected equal distances with equal velocity?'') leads Laura to repeat the experiment in Cycle 6, yielding the same result:

> Laura: [collides them again] Yeah, they go out about the same distance back.
> Hal: So, are we secure on our finding that, uh, when one of them is at rest and the other one is moving that the one that was moving becomes at rest and the mov–, the rest one is moving? Is that, is that gonna happen all the time? As long as . . . what? As long as. . .. As long as the path of the moving one is directed toward the center of the. . ., the center of the resting one, that's gonna happen?

Here Hal is clearly in theory–response mode. He restricts the ''one will stop'' theory to include explicitly the conditions that one of the objects must have been at rest initially, and that the incident object must be ''directed toward the center'' of the resting one. They have, in fact, seen another limitation—that the theory does not apply when the two colliding objects do not have the same mass (Cycles 2 and 3), but they have attributed its failure there to an off-center collision. His question forms the *intention* for Cycle 7, shown in Figure 4 and they repeat the experiment from Cycle 1 (a single puck colliding with a single, stationary one), yet again with the same result:

> Hal: It sure did, didn't it. That's a good enough example for me. It did stop. It sure did. Wow.
> Susan: That's because the momentum of one was transferred into that one, and that momentum was transferred into that one. The resting momentum was transferred to the moving block and the moving mo–, stuff got put into this one. . .. So they like switched places.
> Laura: So if we do one slow and one fast, will they switch again?
> Susan: They should, yeah.

This time, however, Susan's *processing* of the *system response* extends beyond Hal's *perception* that ''It did stop'' to an *interpretation* of the response as an exchange of momentum between the two colliding objects, a key step in the refinement of the theory. The theory-in-action now becomes ''Two colliding objects will switch momenta in the collision.''

The result no longer agrees with Laura's understanding of conservation of momentum in collisions and, for the first time, she makes a suggestion for what they should test next: ''So if we do one slow, and one fast, will they switch again?'' She may have been genuinely curious about the outcome, or she may have expected that the outcome of the asymmetric case would immediately prove the theory wrong.

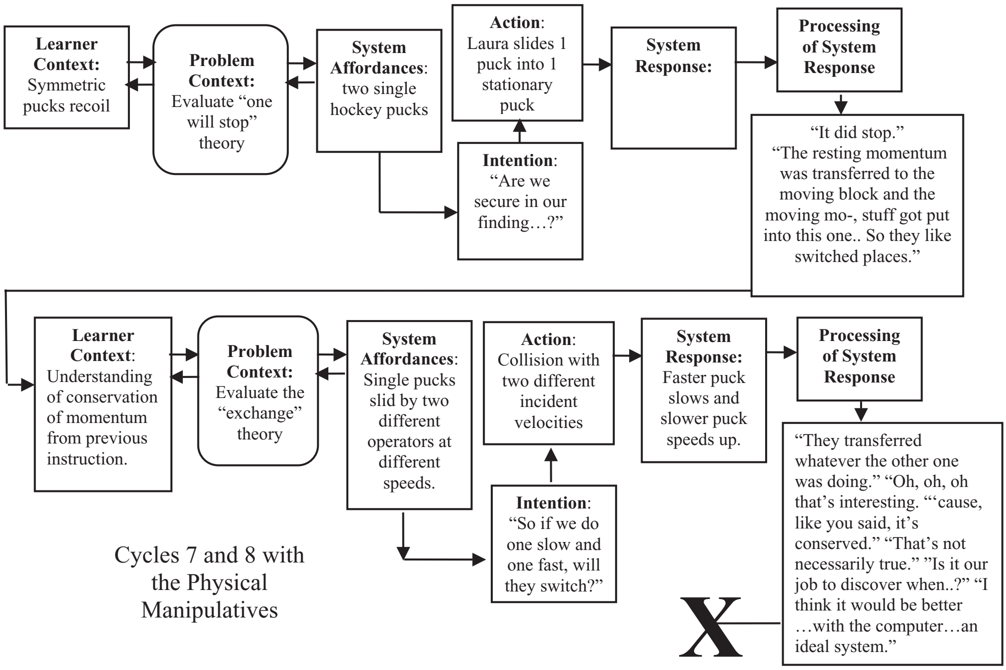

Figure 4. Cycles 7 and 8 with the hockey pucks. The continuing cycle of exploration is interrupted by Laura's insistence on moving to the computer, as indicated by the "X."

Susan makes a prediction that the pucks will again switch momentum with each other and the process continues into Cycle 8, as shown in Figure 4. It takes them about a minute to figure out how to arrange the asymmetric collision, but when they do, the result appears to confirm the theory:

Hal: The faster one . . .
Susan: Slowed down and the slower one sped up.
Hal: Sped up. Slowed down. Right. Right.
Susan: They transferred whatever one is doing into the other one.
Hal: Oh, oh, oh. Oh, that's interesting.
Susan: That's 'cause, like you said, it's conserved.
Hal: Yeah, but I didn't realize that the momentum of one went into the momentum of the other and the momentum of the other . . .
Laura: That's not necessarily true. It's just that the system is conserved.
Hal: The system is conserved so that they don't each swap momentums. They don't swap momentums.
Laura: It's not necessary.
Hal: Not necessarily. There are conditions where that could happen, but . . . . So are we, is it our job to discover what, what conditions it . . . there. You think that we're going too far with . . . with the . . . There's a certain amount of inaccuracy built into this sys–, this measureme–, into this model. Do you think that, with this model, we can come up with the conditions that would allow us to determine when?
Laura: I think it would be better for us to do it with the computer, so that we could have an ideal system.

Here the *learner context* again exerts its influence. Susan makes a reference to Hal's earlier statement that all he remembered about momentum, from his previous instruction in physics, was that it was conserved. Hal responds that this was not how he had understood conservation before, but the notion of exchange is clearly more appealing than his previous understanding, leading him to wish to pursue it further. The *learner context* of Laura's physics expertise, on the other hand, acts in the opposite direction, to curtail pursuing the exchange theory. The identification of "momentum being exchanged" with "momentum being conserved" does not align with Laura's understanding of the standard physics concept of conservation of momentum—that the total momentum of an isolated system must be conserved, but that the momentum after the interaction may be distributed in any number of ways. She invokes her expert status (recall that she is a graduate student, with a double major in physics and engineering) to terminate the exploration by stating that the exchange theory is "not necessarily true," without indicating what the limitations on this theory might be (i.e., that it is only true for elastic collisions in which the objects have equal masses). She follows Hal's lead in asserting that the limited *system affordances* of the hockey pucks may be leading them astray, once again implying that what they observe happening is not necessarily the "right" answer about what happens in collisions. The computer simulation, on the other hand, is expected to embody this canonical response. The iterative development of the exchange theory is interrupted here, as indicated by the "X" in Figure 4.

Cycles 9–11: "Sticky Means Spin"

Laura's assertion that they should move to the "ideal" computer system temporarily breaks the cycle of development for the exchange theory. The group returns again to the catalog of possible experiments within the system affordances of the hockey pucks, implementing several cycles of experimentation with the "sticky" pucks. They have difficulty getting the pucks to stick together permanently—that is, to create a completely inelastic collision. They finally are able to get the pucks to stick in a glancing collision, which sets the pucks spinning and results in a theory that collisions with sticky pucks will result in spin. Susan then demonstrates that pucks with Velcro will stick and not spin if they hit head-on with low relative velocity. Susan then modifies the theory, suggesting that any glancing collision will produce spinning (rather than any collision between the sticky pucks), and a test with the non-sticky pucks proves her right. Laura suggests that they might better perform this simulation on the computer also, and Hal indicates surprise that the computer would be able to do anything so complicated.

Cycles 12–15: "Exchange" Resurfaces

Hal then suggests that they test one more possibility with the non-sticky pucks: one puck colliding with a stationary stack of two pucks. In their estimation, the incident puck stops, harking back to the exchange theory-in-action. (In actuality it rebounds very slightly, but the velocity is so low that friction with the floor brings it to a stop almost instantly.) Then, without any statement of intent, Hal reverses the experiment, colliding the two-stack with a single stationary puck. Although he does not seem to be explicitly aware of it, this is the same situation as in Cycle 2 and 3, given earlier. In this case, the collision is clearly dead-on, and the incident puck clearly does not stop as a result of the collision. Hal takes immediate note that the exchange theory has been violated:

Hal: Why didn't it stop that time? Why didn't the first one, the heavier one, stop?
Susan: I don't know.
Laura: It won't stop completely.

Hal: And why? Why not? I thought they did. I thought one of them?
Laura: You're just conserving through the system.
Hal: The system. So that, aah, when that one stopped it was just a coincidence? That the one always stopped? Remember when the two were equal? The two had equal mass? That was a coincidence then?
Laura: It was because of equal mass. That was only happening when we hit it right on dead center.
Hal: Okay. Okay. [He repeats the experiment, sliding the stack of two pucks into the single puck in a glancing collision.] That wasn't dead center. Right. Okay, try dead center. [He slides the stack of two directly into the center of the single puck.]
Laura: Here, we should be able to try those a lot better with the computer.
Hal: So, we need a computer.
Susan: We got one.

Laura interprets the results by saying that, ‘‘You are just conserving through the system,’’ without explicitly acknowledging that having the two colliding objects exchange momentum is one way (in fact the only way in the case of equal mass objects in elastic collisions) for the system to conserve momentum; that is, to keep the total the same before and after. Hal has identified the salient restriction that the exchange theory only works in cases in which the colliding objects have equal masses, but thinks in terms of a coincidence, rather than a restriction to the theory. Laura concurs that the exchange seen before was ‘‘because of equal mass’’ when ‘‘we hit it right on dead center.’’ Hal picks up the latter limitation and repeats the experiment twice. The first time results in an off-center collision, but the second is clearly dead-on. The incident puck clearly continues moving after the collision, but no one comments on this result. Instead, Laura collects the pucks and once again asserts that the computer will be able to inform them on the truth of the matter, ending their exploration with the physical manipulatives. At this point the instructors call for a rotation of roles and, after a brief discussion of who should have what role, they decide that Hal should be the recorder, Laura the designer, and Susan the operator. The group moves to the computer, where Laura already has the program running.

Summary

With the physical manipulatives, the group moved quickly through the experimental cycles, each a seemingly obvious follow-on to the previous cycle. They took, on average, about a minute per cycle. Some cycles, particularly the last two in which Hal repeated Cycle 13, took only a matter of seconds. The transcript segments are fairly typical of how the group processed the results of the experiments, with Hal and Susan making and confirming each other's statements about what they saw and Hal asking the others why the results did not confirm his expectations, and whether they needed to perform more tests. Most often this resulted in a repeat of a previous experiment (to confirm its results) or an additional test from the catalog of possibilities, as when Susan suggested the head-on collision, Laura suggested one slow and one fast, or Hal suggested one puck colliding with two stationary pucks. On three separate occasions, it resulted in Laura directing the group toward the computer.

Results of Theory Development With Interactive Physics

Cycle 1: ‘‘Exchange’’ Tested in the Simulation

Table 2 describes the cycles of theory development that the group enacts with the computer. In Cycle 1 with the computer, the group's stated *intention* is simply to ‘‘just recreate these’’ (the

Table 2
Experimental parameters, outcomes, and theories generated or tested for the cycles of exploration with the computer simulation

Case	Object 1	Object 2	Elasticity	Outcome	
1	1 moving	1 stationary	0.5	#2 moving with 3 × velocity of #1	Exchange (fails)
2	2 moving	1 stationary	0.5	#2 moving with 2 × velocity of #1	Ratio of velocities
3	3 moving	1 stationary	0.5	#2 moving with 1.8 × velocity of #1	Ratio of velocities
4	1 moving	2 stationary	0.5	#1 stops, #2 moves with 0.5 incident velocity	Ratio of velocities
5	1 moving	1 moving, same speed, opposite direction	0	Pucks meet, stop, stick briefly, and then slowly drift apart	In an equal mass, equal speed, dead-on, inelastic collision, the objects will come to a stop (fails)
6	1 moving	1 moving, same speed, opposite direction, glancing collision	0	Both pucks spinning afterward	A glancing collision means spin
7	1 moving	1 moving, same speed, opposite direction, glancing collision	0.5		A glancing collision means spin

conditions from Cycle 1 with the physical manipulatives); however, they also want ‘‘an ideal system,’’ and Susan, who is now the operator, invokes the *system affordances* to set the computer ‘‘world’’ to ‘‘no gravity’’ and turn off friction. Laura had been experimenting with the program earlier, and she gives instructions to Susan. Despite this, it takes some time for Susan to create the two pucks in the simulated environment, set them moving with reasonable velocities, and figure out how to display their velocity parameters before and after the collision, before they are ready to run the simulation (*action*).

They believe that they have an ‘‘ideal’’ version of the earlier experiment: one hockey puck colliding with another, single puck, in a frictionless, completely elastic collision; that is, with no conversion of kinetic (motion) energy into other forms of energy. Laura reiterates that the apparent exchange seen before ‘‘was because of our frictional surfaces. . .. It will be different here.’’ If they had actually recreated the first collision with the hockey pucks, with no change except removing friction, the *system feedback* would once again have confirmed the exchange theory, most likely leading to further refinement.

There is, however, an inadvertent but more significant difference than friction between the physical and computer experiments. With the hockey pucks, the collision was very nearly perfectly elastic (elasticity of $\sim$1), but the computer simulation is now using its default setting (elasticity equals 0.5), meaning that half the kinetic energy is converted to other forms in the collision (see Appendix). The group had been given a handout instructing them to set the elasticity of both objects to 1 for elastic collisions and to 0 for inelastic collisions, but they leave the elasticity at the default setting with no discussion. At this point, they are apparently unaware that they have not created their ‘‘ideal system’’ of a perfectly elastic collision, and the *system affordances* clearly affect the progress of the investigation.

The *system feedback* is undeniably in violation of the exchange theory-in-action, which is apparently still viable for Susan and Hal. Both objects are moving after the collision. Susan immediately objects, *evaluating* the *system feedback* in terms of the exchange theory:

Susan: This one should stop.
Laura: This one shouldn’t stop. It shouldn’t change with the way it’s [inaudible]. They won’t ever stop completely.
Susan: Oh, ‘cause there’s no gravity?
Laura: Right.
Hal: And friction.
Laura: There’s no friction and no gravity.

Here Laura omits her earlier assertion that exchange was ‘‘because of equal mass. . .when we hit it right on dead center.’’ She asserts once again that the stopping before was due to friction and gravity, rather than the interaction with the other puck. (This is despite the fact that in the physical experiment they saw the incident puck come to rest instantly, as opposed to slowing down over a distance as one would expect from a frictional effect.) At this point, the group seems to agree with her. Susan and Hal are willing to concede that the apparent exchange behavior they witnessed previously was, in some unexplained way, the result of friction and gravity.

Cycles 2–3: “Ratio of Velocities” Theory

Having apparently abandoned their exchange of momentum theory-in-action, the group moves on to an experiment in which the incident object has twice the mass of the stationary object. Thus, Cycle 2 with the computer is analogous to Cycle 2 with the physical manipulatives, except that the elasticity is now 0.5 and there are no frictional or gravitational effects. Once again, the result is that both objects are moving after the collision.

At this point, the only theory-in-action that the group generates while using the computer simulation begins to develop. Once again, an observation by Hal is the source of the theory. In *processing* the *system feedback*, Hal notices that, in this case (mass ratio 2:1), the final velocity of the lighter, initially stationary, object is precisely twice that of the heavier, incident, object. Looking back over their data, he notes that, in the previous case (Cycle 1, with a 1:1 mass ratio), the outgoing velocity of the initially stationary object was also a "multiple," exactly three times the outgoing velocity of the incident object:

Hal: It's just a coincidence that this is going, uh, twice as fast? In this case the final velocity.
Laura: That's 'cause it's . . .
Hal: This was a multiple, though [referring to the previous experiment, Cycle 1 with the computer], this was twice the velocity of the first one, actually, correct, actually three times the velocity. That's the initial velocity. Final velocity. . . . Yeah, final velocity is.

Laura then provides an *interpretation* for Hal's "ratio of velocities" theory: because one puck has twice the mass, the other puck must have twice the velocity. Interestingly, that would have had to be true only if the puck with twice the mass had exchanged momentum with the other as a result of the collision. Here the 2:1 velocity ratio afterwards is simply the result of the restriction that they have inadvertently imposed, the default condition that half the kinetic energy is lost in the collision (see Appendix). Laura does not explain how the inverse relationship she asserts between mass ratio and velocity ratio would account for the 3:1 velocity ratio in the previous case with a 1:1 mass ratio.

They decide to test the theory-in-action that the ratio of the velocities after the collision will be a whole number as long as the ratio of the masses of the colliding objects is a whole number by making the mass of the incident object three times the mass of the stationary object (*evaluation*). Although they do not make an explicit prediction of what the ratio of the velocities after the collision will be in this case (*extrapolation*), the resultant ratio (1:1.8) does not fit the expected whole-number pattern:

Hal: So the ratio between velocities is not a simple one.
Laura: No, it's, we've got a ratio of 1.8. We started out with ratio 3, then 2, then 1.8.
Hal: Oh, no, that's right. . .
Susan: Maybe our mass isn't exactly. . . . What's 3.142 times 3?
Hal: Two to one. . .
Laura: 9.426. No, we should be getting the right answer. We should be winding up with a square relation.
Hal: The velocities ratio is three to one, two to one, and 1.799.
Susan: The momentum is different too.
Hal: Yeah, yeah.
Susan: Okay, let's try the ones where they stick together.
Hal: I get 1.7, oh, wup, up, up– I get 2.9? Are you sure? Because 2.9 and 1.7 don't add up to 4.1.
Susan: 4.713.
Laura: 4.713. I think this 4.713.
Hal: Oh. Four point . . . 4.713. I reversed two values. 4.713.
Laura: Does that add up, okay?

Hal: Yes.
Susan: Now we are gonna make ‘em stick, yes?
Laura: Do we want to make them stick, or do we want to try one more mass?
Susan: It’s just, it should just be a logarithm, right? An exponential.
Laura: Let’s try 2:1. Make . . . Let’s try making this one heavier.

The lengthy time spent repeating values and calculations and confirming them with each other is typical of all exploration with the computer. Note that Laura seems to have an idea that there should, indeed, have been a pattern in the ratios of the outgoing velocities (a ‘‘square relation’’), but she does not provide an *interpretation*. She does seem to want to pursue further the pattern in the ratio of velocities after the collision, but Susan does not. Susan asserts that they know that the relation should ‘‘be a logarithm’’ or an exponential without any indication as to why this should be true (and no sign of such a relationship in the data). She may be referring back to Laura’s assertion that it should be a ‘‘square relation,’’ and thinking that a square relation is a kind of exponential relationship because it involves an exponent.

Cycle 4: “Exchange” Surfaces, Yet Again

This time, Laura has provided the *intention* for the next cycle, Cycle 4 with the computer, suggesting that they give the stationary puck twice the mass of the incident one in order to investigate further the ratio of the velocities after the collision. It takes them some time to set up one simulated puck with twice the mass of the other one. Recall that the group performed this experiment with the hockey pucks also, but in that case the elasticity was close to 1. Before, the incident object rebounded very slightly, but friction quickly brought it to a stop and, in their *perception*, the incident object stopped as a result of the collision, in accordance with the exchange theory. Here, the computer program is setting the elasticity to 0.5 by default. For this case, with 0.5 elasticity and the stationary puck having twice the mass of the incident puck, once again the only way for both energy and momentum restrictions to be met is for the incident object to stop and the stationary object to continue with the momentum originally possessed by the incident object. By coincidence, they have arranged another case in which the colliding objects will exchange momenta:

Hal: Do we want to change the velocities or something?
Susan: This one heavier?
Laura: No.
Susan: This one heavier?
Laura: Make this one double and this one back to 3.142.
Hal: She’s the designer.
Laura: You can be the designer, but I want to play with it.
Hal: You want to play with the mass of the, still the mass? Is that what you said?
Susan: 3.14?
Laura: Of the second one. This one is 3.142 and this one’s 6.284.
Hal: 6.284.
Susan: And this one’s still colliding with this one?
Laura: Yep.
Susan: 1.571 is initial momentum. [Pause] And guess what? This one completely stops, and this one keeps going with the same momentum [that the other one had before the collision].
Hal: Okay.
Susan: That’s what we said wasn’t it? [inaudible].

Again, the extensive discussion involved in setting up the experiment and confirming what parameters are needed is typical of the exploration with the computer. Susan's *perception* is that, once again, the objects have exchanged momenta, reviving the earlier theory-in-action. This time, there is no protest from Laura. Hal continues to look for a pattern in the ratio of velocities. This is not possible because one of the velocities after the collision is zero in this case, but he notes that the heavier object's velocity afterwards is half the lighter object's velocity before the collision. Laura notes that this is simply because the originally stationary object now has the momentum that the incident object had previously and, because it has twice the mass, it must have half the velocity for the product of the two to remain the same. The group does not pursue further the pattern in the ratio of the velocities after the collision, and it is not reflected in their final report.

Cycle 5: The Computer Betrays Susan

The group then decides to simulate the classic case of an inelastic collision between two equal-mass objects moving at each other with equal speeds (opposite velocities). It takes them some time to set the parameters in the simulation to create objects with appropriate properties for this to happen. This is a staple of physics demonstrations and homework problems, and the accepted rules of physics predict that the two objects will stick together and come to a dead stop. Because their momenta were opposite before the collision, and thus the sum was zero, the total momentum after the collision must also be zero. Susan had been looking for this result with the physical manipulatives, but was not able to achieve it because of the difficulty of getting the pucks to stick together in a head-on collision. She expects that the superior *system affordances* of the computer will yield this dramatic result. What the simulation shows, however, is that the pucks hit and then slowly drift apart:

Susan: It didn't stick! It didn't stick together!
Laura: It doesn't . . .
Susan: Don't . . . momentum goes to negative .035 of circle one. Velocity goes to . . .
Hal: That must be some inaccuracy in the program, don't you think? 'Cause they should have stopped if they're the same velocity, and had, directed toward each other.

Note that Hal has the same expectation as Susan. They discuss the possibility that the computer cannot handle the zero elasticity "because computers can't divide by zero," and, after some time computing and adding the momenta, they agree that the final momentum is indeed very close to zero. Laura is able to accept this as the result of a collision that was not perfectly inelastic, but Susan is not:

Laura: And the reason these were not working out is because it's not a perfectly inelastic collision either . . . that's what those . . . that makes much more sense to me now.
Hal: Oh, I see . . . final velocity . . .
Susan: See, this would hinder students' future learning [inaudible]. 'Cause this shows that they're separating apart, but they don't.
Hal: [laughs] Uh, huh. That's your observation.
Susan: All this is teaching me is to never use the computer in my classroom.
Laura: Oh, but this thing's so cool.

Laura continues to demonstrate all the ''cool'' things the program can do. She proceeds to demonstrate that she can make the simulated computer pucks spin in a glancing collision. Susan accuses her of being ''such a physics major'' and complains to the instructor that ''[w]e don't like the program because it's wrong.'' She continues to make her case to the instructor, again noting the simulation would ''hinder students' future learning.'' Hal notices that Laura has indeed been able to recreate, on the computer, the case where a glancing collision between sticky pucks causes them to start spinning. He asks, ''So, if they get off-angle, some of it's not going to be conserved, to be converted into, if they're sticky, if there's . . . ah, boy.'' She responds by repeating the experiment and demonstrating that the pucks do indeed conserve both total linear and total angular momentum.

The group does not complete any more cycles of investigation, despite the fact that there was more time available in this class period, and time for additional inquiry was also available in the next class meeting. At this point, they debate the merits of the program and then begin to discuss whether they have achieved the goals of the exercise—that is, to find out what happens to the momentum of objects in collisions:

Laura: We demonstrated conservation of momentum, right? And we demonstrated that angular momentum [inaudible].
Susan: Then we found there's a glitch in the system.
Laura: That's all you will remember isn't it?
Susan: Because as soon as something, as soon as something betrays me, I never look at it again.
Hal: Now what was . . .? So the conclusion was, that they're both gonna, even if one of them is stationary and the other one is moving, that they are both gonna be moving afterwards?
Laura: Right.
Hal: Afterwards. That's the general finding. Okay.
Laura: But that the one will slow down.
Hal: And that's caused because of elasticity, or difference in elasticity? What if, what if . . .?
Susan: If it's inelastic, then it'll stop.
Hal: If it's inelastic.
Susan: If it's elastic, they'll keep moving, very slowly and this one goes off . . .
Hal: That's what it is. Elasticity causes them to . . .
Susan: 'Cause it's like boi-oing, like a spring.
Hal: So if it's inelastic, then the first one will stop and the second one will continue to move. Ah. That makes sense.
Laura: In a new direction completely.
Hal: Okay. Allright. That makes it sort of presentable.

Note that, as they grapple with what they have learned, Hal focuses on the case that disproved the exchange theory. Now he blames the failure of the theory on elasticity. Susan corrects him to say that in a (perfectly) inelastic collision, ''it'll stop.'' She is thinking of a different case, presumably between objects with equal but oppositely directed momenta, where the computer betrayed her. Hal interprets this inelasticity as the reason they thought the pucks exchanged momentum. It is not clear what Laura means by, ''In a new direction completely.'' They are all talking past each other, but each has achieved a result that he or she can live with. Susan is even satisfied that elasticity is a reasonable explanation for the computer's anomalous behavior, because, if the objects are slightly springy, they will bounce away from each other, despite having declared that she will never look at it again.

Summary

With the computer simulation, the students completed a total of seven cycles of exploration in all. Each computer exploration was accompanied by laborious exchanges of information about the parameters and calculations. In the first cycle, designed to test the exchange theory, the ''ratio'' theory was generated. This was the only theory that arose solely during exploration with the computer and it continued for three cycles. In the last of these, the exchange theory was resurrected. The group then attempted to produce the classic case of a dead-on collision in which two objects stick together and, finally, reproduced the result that a glancing collision will cause the pucks to start spinning. Once again, observations by Hal and Susan provided the genesis for a theory-in-action, but in the case of the ratio theory, Laura was the one who pressed for testing the theory further.

Presentations and Posttest

After the explorations were completed, each group presented its results to the entire class. Hal presented the results for his group. He first made the point that his knowledge, as experiment designer, ''put a limit on the types of variables that could be discovered.'' He then reported their findings with regard to momentum (J.M. is the instructor):

Hal: Uh, the designer first wanted to test, uh, uh, stationary versus moving object, and, uh, we found that the stationary one stopped and the secondary one moved with approximately the same velocity. Then . . .

J.M.: And were those equal-mass items?

Hal: They were equal-mass items, yes. And, uh, non-sticky. And uh, then, uh, with the same mass and stickiness, we wanted to try uh a collision with both of them heading towards each other with the same velocity. And that, uh, after, fi– uh, several, uh, attempts where there were nondirect collisions and both of them kept moving, uh, we discovered that they would both stop, approximately stop if the collisions were, uh, head, uh, on center. So that sort of, uh, reestablished of feeling of, uh, that, uh that there was something canceling something out, or the conservation of momentum. And, uh, then we went on to, uh, doubling the masses, of one, and seeing what would happen. Uuh, uuh, the designer sort of expected that, uh, a similar thing would happen, that the first one would stop and that the second one would go twice as fast. Which is one possible expla–, uh, expectation, but it's, uh, the results seemed that both of them kept moving in this particular situation. Uuh, . . . uh . . . don't know why.

Clearly, Hal did not leave the exploration process with a robust understanding of conservation of momentum. In fact, his statement that he expected the collision between objects with different masses to produce an exchange of momentum, and (still) did not know why that did not happen, indicates that the exchange theory still resonated with him.

His response on the posttest gave the same indication. The posttest was administered in the class period subsequent to the presentations. The test described a frictionless collision between two non-sticky hockey pucks, one with a mass of 10 kilograms and a velocity of 2 meters/second to the right and another with a mass of 3 kilograms and a velocity of 5 meters/second to the left, and asked students to describe how they expected the objects to be moving after the collision. Hal began by writing, ''They will be moving away from each other in a directly opposite path,'' but then crossed out that statement and wrote ''both to the right, with the 3 kg one moving farther.'' Note that his first response is what would have happened had the two objects exchanged momenta.

His second response parallels what happened in the (to him, anomalous) collision between two pucks of different masses—that is, that they both were moving in the same direction after the collision.

On her posttest, Laura wrote that she ‘‘assume[d] conservation of energy,’’ followed by two equations, one indicating that sum of the momenta before the collision would equal the sum of the momenta afterwards, and one indicating that the sum of the kinetic energies before the collision would equal the sum of the kinetic energies afterwards. She then attempted to solve the two equations simultaneously, but was unable to work through the algebraic manipulation required to reach a solution. Her response relied strictly, but unsuccessfully, on prior knowledge. Susan was absent and did not complete a posttest.

Differences in the Exploration Process

Using the Land and Hannafin (1996) framework, we identified 15 iterative cycles of theory development with the physical manipulatives, 13 with the non-sticky hockey pucks and 2 with the sticky pucks. With the computer, there were only seven cycles. Thus, even discounting the two extremely short cycles at the end, which Hal enacted alone, the group completed nearly twice as many development cycles in the physical testing environment as in the computer simulation environment, despite the fact that they spent approximately twice as much time on the computer.

This was partly because the group simply took longer to do things using the computer than they did with the physical manipulatives. For example, completing the *action* portion of the first exploration cycle with the computer took them almost three times as long as figuring out how to execute the dead-on collision between two pucks with different velocities (the *action* portion of Cycle 8), which took the most time of any of the physical experiments. *Processing* of *system feedback* also took the group longer with the simulation. They processed the results from the physical experiments very quickly, generally by remarking how far and in what direction the pucks had traveled on the floor before friction brought them to a stop, and then correlating that with the velocity after the collision.

In contrast, the group at times appeared to be stuck in the *processing* portion of the cycle during the computer experiments. For example, *processing* the *feedback* from Cycle 1 on the computer involved 11 exchanges between members of the group compared with only 2 or 3 exchanges for the typical physical experiment cycle. Although one might expect these exchanges to be profitable in the refinement of the theory-in-action, as the group tried to develop an explanation for what they saw, these exchanges were generally limited to perception, rather than interpretation, evaluation, or extrapolation. In each cycle, the other group members had to ask Susan, the operator, what parameters she had entered into the simulation and what parameters resulted from the collision. They then generally repeated these for confirmation, often more than once. The limited field of view of the computer screen contributed to this phenomenon because the screen size required one person to report the results to the others, a tedious process requiring several iterations for confirmation. Limitations on the computer’s ability to support interactions between more than ‘‘2 or 3 students’’ have been noted previously (Roth, Woszczyna, & Smith, 1996, p. 1007), and here it posed a barrier even for a group of three users.

Likewise, mathematical calculations that the group had to perform in their heads took up considerable time. For example, calculating what to set the mass of the incident puck to so that it would be two times the mass of the stationary puck, or what the ratio of the velocities was, generally required several iterations, and prompted a comment by Susan that, ‘‘Calculus is over. No more math for me.’’ With the physical pucks, doubling the mass was a simple matter of stacking the second puck on top of the first, taking less than a second, and judgments of relative velocities, while qualitative, were essentially instantaneous.

In addition to being shorter, the cycles of theory development in the physical environment were more productive in terms of leading to theory refinement. Generally, *processing* of *feedback* from one cycle led to an *intention* or *action* to test and refine the theory in the next (as opposed to cycles with the computer, in which processing of feedback generally led to more processing of feedback). The chain of refinement, begun in Cycle 1 (Figure 2) and continuing in Cycles 2 and 3 (Figure 3), went on for a total of eight cycles. The group solidified and refined the exchange theory at each pass until Laura put a stop to what she saw as a dead-end exploration, in conflict with the accepted theory of conservation of momentum. The shortest run of cycles with the physical manipulatives (three cycles for the "sticky means spin" theory) matched the longest with the computer (three cycles for the "ratio of velocities" theory).

Results of the transcript coding also confirm a shift in the structure of the development cycles as the group moved from the physical manipulatives to the simulation environment. While doing physical experiments, 38% of the group's statements coded as *actions* or *intentions* and 48.6% as *processing* of *system feedback*. As the group moved to the simulation environment, this changed. Only 13.1% of the statements referenced *intentions* or *actions* and 59.5% reflected *processing* of *system feedback* or parameters. A chi-square analysis of the two samples (statements made while using physical manipulatives and those made while using the computer simulation) for three categories (*action/intention*, *processing*, or *neither*) yielded a chi-square value of 40.81 ($p < 0.001$), indicating that the behavior was significantly different statistically.

One might argue that the shift toward spending a larger percentage of time in the processing part of the theory development cycle is only the natural result of the availability of more precise feedback with the computer simulation: there is more information to process, and therefore the group spends more time processing it. However, the computer also could have allowed for more detailed planning and implementation of experiments and more parameters to vary, yet the group did not really avail itself of these affordances. The number of statements dealing with intents or actions decreased not just as a percentage of the whole, but also in absolute terms, even though the group made many more statements while using the computer.

Effects of System Affordances

As in previous studies (Roth, 1995; Roth et al., 1996), the computer was found to be a "tool unready-to-hand" for the group studied here. Although the affordances of the computer system allowed these students to do many things they could not do with the physical manipulatives, doing anything with the computer took much longer. Furthermore, the group sometimes misunderstood what they were doing and seeing on the computer. For example, they believed that the default elasticity setting must correspond to a perfectly elastic collision, resulting in missed opportunities. This was true despite what were considered to be very explicit written instructions from the instructors, and a tutorial designed to familiarize the students with the program.

The affordances of the respective systems also dictated the kinds of theories-in-action that the group developed. With the physical manipulatives, the group could only generate theories that arose easily from qualitative observations. Both the exchange and "sticky means spin" theories arose from a readily visible physical process. In case of the exchange theory, this visibility led Susan and Hal to extend their observation to an explanation—that is, the final momenta are what they are *because* objects exchange their momenta when they collide.

Such theories, although limited, may operate along the lines of "phenomenological primitives" (Di Sessa, 1993), extremely intuitive and deeply held beliefs that tend to arise from everyday physical experience, making them common among learners. The exchange theory was also generated by other students in the class during this same activity and has been seen at other institutions among students working with physical manipulatives (Marshall, 2002; O'Brien-Pride, 1997). These conceptions are also very robust. The exchange idea reemerged time and again in the work of the group we studied, despite the best efforts of their *de facto* expert to steer the others away from it. At the end of the computer experiment, Hal was willing to accept the conclusion that, even if one object is stationary before the collision, both objects might be moving afterwards. In the next class period, however, his report still included that he expected one object to be stopped afterwards, and that he did not know why that did not happen, although he did not specifically mention the exchange theory. On his posttest, he also initially wrote a result consistent with the exchange theory, but then marked out that response.

One might argue that the exchange theory could also have arisen with the computers had the group experimented in that environment first, but the affordances of the simulation system worked against this. When the group simulated the obvious case of one puck sliding into another identical, but stationary, puck, they unintentionally modeled a semielastic collision, and thus did not see the revealing case in which the pucks appeared to exchange momentum until later in the exploration. At that point the group noticed the exchange, not so much because the incident puck dramatically stopped, but rather because it confirmed what they had asserted before (''That's what we said wasn't it?'').

In fact, the only theory that originated in the simulation environment was based solely on a *mathematical* relationship that the group perceived in the system feedback. The precise output provided by the Interactive Physics program allowed them to recognize that the one of the outgoing velocities was a multiple of the other in the first two cases they examined, and yet there was no process readily visible in the collision to account for this observation. Laura's statement that the ratio of the velocities after the collision should involve a ''square relation'' may have been related to the kinetic energy construct ($0.5mv^2$), but she never made that explicit. She was undoubtedly aware of the concept from her physics courses and demonstrated awareness of its relevance in her posttest.

The kinetic energy has no immediate physical referent, and therefore the group could not readily tell what was happening to the kinetic energy by observing the simulated pucks on the computer screen, where the physical interaction was modeled. Interactive Physics actually affords the user the opportunity of displaying the kinetic energy as part of a pull-down menu of measurable parameters. The affordance of displaying both the phenomenal (interactions between simulated physical objects) and the conceptual (abstract constructions of the science community) in the same space, and thus coordinating the two domains for the novice observer, has been cited as one of the strengths of learning with computer simulations (Roth et al., 1996). The group we studied, however, saw no need to seek to display the kinetic energy, apparently believing that, in the default setting, it should be required that it be conserved.

Thus, they could not see what was happening to the kinetic energy, and did not realize that it was not being conserved. Without this knowledge, there was little hope of their unraveling the interaction between the constraint of conservation of momentum, which the program requires in the absence of external forces, and constraint that the default elasticity setting of 0.5 puts on the change in kinetic energy. It is this complicated interaction that determines velocities after the collision (see Appendix). One final velocity happened to be a multiple of the other in the two cases they first simulated, but not in all, as the group soon found. Not being able to develop an explanation for why the velocity ratios after the collision should be as they were, the group soon abandoned the ratio theory and it never reemerged. Hal did not mention it in their final report. In the end, the group did not benefit from the enhanced affordances of the simulation environment to provide feedback about experimental parameters because they were not able to capitalize on these affordances to refine their theories-in-action.

Likewise, the group did not take advantage of the affordances of the computer to test virtually limitless combinations of masses and incident velocities for the colliding objects. They only tested one case with the computer that they were not able to test with the hockey pucks (the 3:1 mass ratio) and some groups were able to create this case with the physical manipulatives by borrowing a puck from a neighboring group. In fact, the group tested several cases with the hockey pucks that they did not test with the computer. This was not due to time constraints. Although processing feedback from the system took more of their time, they still had time to complete more simulated experiments at the end of class, but seemed to feel that they had all the data they needed to answer the question of what happens to the momentum of objects in a collision.

Effects of Learner Context

Clearly, learner context was a determining factor in these prospective teachers' ability to use both the physical and simulated environments for productive exploration. Laura's existing formal knowledge in physics, and her accepted role as the physics expert, seemed to get in the way of productive exploration. She was willing to let the exchange theory develop, and even suggested an extrapolation of the theory (''So, if we do one slow and one fast, will they switch?''), until Susan equated ''exchange'' of momentum with ''conservation'' of momentum, at which point she terminated the exploration by diverting them toward the computer (see Figure 4). Much like the physics teacher in the study by Roth et al. (1997), she believed she knew what conservation of momentum means, and saw her role as guiding the others to arrive at this canonical understanding and preventing them from pursuing ideas she felt might ultimately place them at a disadvantage. In this role, she did not expect to learn anything herself from the activity. She subscribed to the students' fundamental dilemma that ''the correctness of the knowable in their laboratory exercises is prefigured in advance'' (Roth et al., 1997, p. 128), and is not to be discovered through their own exploration. She claimed that it would ''be better for us to [test the exchange theory] with the computer, so that we could have an ideal system,'' but her expectation was that the computer would confirm what she already knew, rather than expand her knowledge. For her it is a toy rather than a tool.

Even so, had the group been able to replicate successfully the hockey pucks experiment on the computer, they would have validated the exchange theory once again, and probably forced Laura to confront the gaps in her own understanding. Because they were not able to take advantage of the system affordances of creating a perfectly elastic collision, she lost out on an opportunity to explore the role of elasticity in the exchange theory and come to the recognition that, in order to conserve kinetic energy (perfectly elastic collision), the only way that momentum *can* be conserved in a collision between two objects of equal mass is for them to simply switch their momenta. Because conservation of energy and conservation of momentum are generally taught (and tested) separately in physics courses, students rarely have to confront a case in which they have to take both into account. Instead, they are provided with additional constraining information, or are only asked to look at limiting cases. Likewise, by carefully structuring questions, common instruments used to test understanding of conservation of momentum and energy never force students to confront both issues at the same time (Graham & Berry, 1998; Singh & Rosengrant, 2003). The computer simulation could have provided an ideal opportunity for these students to develop a coherent framework for collisions by identifying the role of both energy and momentum in determining the outcome if they had been able to use it successfully.

In Susan's case, prior knowledge (about what ''should'' happen in an inelastic collision between two objects with equal and opposite momenta), and more importantly her attitude toward the computer as a source of authority, likewise interfered with her successful use of the simulation for learning. Once the computer gave them the ''wrong'' answer, she was unwilling to work with it any longer because, in her words, ''As soon as something betrays me, I never look at it again.'' Susan's reaction verifies previous indications that some students can come to view the computer as a source of authority, a replacement for the textbook or instructor, rather than a tool for exploration (Steinberg, 2000). For such students, failure of the system to deliver on expected affordances may be particularly troublesome.

Susan was also denied an opportunity—in her case the opportunity to experience science as a discovery process. Although she was able to construct a valid, albeit limited, theory through her own exploration, the experience was never validated for her. Because the group never reported the exchange theory back to the entire class during the discussion in the next class period, there was no opportunity for this result to be ''discussed, critiqued, and researched so that the phenomenon would come as a social construction of the class'' (Roth et al., 1997, p. 131). Rather, what Susan learned was, ''to never use the computer in my classroom.''

Hal, finally, was a driver for the exploration process, despite the fact that his prior experience in physics was the weakest and most remote. His observations were the original genesis of each of three theories-in-action. He was fascinated by Susan's explanation for the ''velocity one stops'' behavior in terms of exchange, and he argued to pursue this theory (and the others) at every turn. We conjecture that it is also his prior experiences, specifically his *limited* formal instruction in physics, that positioned him for this role. In his novice status, he was perfectly comfortable acknowledging that he did not know what to expect.

On the posttest in this study, every one of the correct answers came from students who, like Hal, were biology majors, and these were the students with the least formal physics training. Recall that Hal also initially had a qualitatively correct answer, but he crossed it out. On the other hand, Hal yielded to Laura as the expert, and was not successful in implementing his agenda of developing a conclusion that he could understand and report with confidence.

Conclusions and Implications

The Theory Development Model

The Land and Hannafin (1996) framework for the development of theories-in-action proved useful in analyzing the work of these three prospective teachers acting as a group. The group's on-task statements and actions were easily classified according to this system, as evidenced by the high level of agreement between the independent coders. Furthermore, using this framework, we were able to quantify the ways the prospective teachers operated with the simulation as compared with the physical manipulatives, illuminating the differences between the two. The *learner context* and *system affordances* were clearly important elements in the work of the group we studied. Coding by these constructs helped to explain why the group operated the way it did, and to point toward what would need to happen to make the process more fruitful.

The Research Questions

(1) Are there differences in the actions of prospective secondary science teachers as they employ physical experimentation versus computer simulation to investigate, collaboratively, physical phenomena?

In this study, there were clear differences in the way the group we studied employed the computer simulation, as compared with the physical manipulatives, for exploration. First, the group took longer to execute cycles of exploration with the computer than with the physical manipulatives. Our analysis also found that, in the simulation environment, the group spent much more time in the *processing* of *feedback* from the program, particularly in actually reading the feedback out, as opposed to the *action and intention* cycle. The enhanced feedback available to them simply resulted in additional processing time, rather than additional cycles of exploration. In the conceptual framework presented by Land and Hannafin (1996) and employed here, it is through progressive *cycles* of theory development, as opposed to extended interpretation and evaluation, that learners refine their theories-in-action.

These findings have clear implications for instruction. First, simulation environments do not necessarily live up to the expectation that they will permit users to vary parameters, obtain measurements, and display results much more quickly, easily, and accurately than they could in physical experiments. In fact, more time may be needed for students to work in the simulated environment as opposed to the physical one. Time will also need to be set aside for explicit instruction in the operation of the simulation to ensure that students are able to use it properly. For the use of such systems to pay off, students are likely to need prolonged and repeated exposure.

A second implication is that instructors should seek ways to refocus learners' attention on theory generation and testing in a simulated environment. This might be done by providing a structure to make this process more overt, as has been done in previous work with simulations (de Jong & van Joolingen, 1998). Requiring learners to state interpretations, evaluations, or extrapolations (as opposed to just perceptions) explicitly in each cycle may lead to more productive refinement of theories.

(2) How do the affordances of the simulation environment interact with the development and evaluation of theories-in-action in a physical science context? Does this interaction have implications for the design of open-ended learning environments?

Our prospective teachers had difficulty using this system, despite their general competence and enthusiasm in use of computers. We found that the group had difficulty in interpreting system input parameters and displays, confirming earlier studies of students using Interactive Physics (Marshall, 2002; Roth et al., 1996). The group apparently did not consider how the elasticity parameter of the simulation was set during most of their work with the simulation, despite explicit directions from the instructors. This misunderstanding impeded the successful development of theories. Once again, the simulation acted as a tool that "draws all of the problem solver's attention onto itself" (Roth, 1995, p. 334) and away from the task of exploration.

The result here is of particular concern because the students in this case were, in fact, poised to be teachers themselves. With little, if any, further experience, these prospective teachers were expected to implement similar technology in their own classrooms. They clearly did not yet belong to the cadre of experts for whom the use of such a system would be transparent and the meaning of feedback obvious, implying that preservice programs, ours included, need to incorporate explicit training in the use of the specific technology that teachers will use in their classrooms. Teachers will need even more time than students to become familiar with the systems in order to design instruction and guide their own students in their use. Opportunities for becoming familiar with such technology would ideally be situated in the content courses taken by prospective teachers, where they might learn the use of the simulations in context.

There are also clear implications for the design of open-ended learning environments. Designers should undertake every effort to make the meaning of the parameter settings obvious for the simulation. Confusion about the meaning of the elasticity parameter in Interactive Physics has been shown to misdirect some students (Marshall, 2002). Although it was possible to create display windows for parameters such as velocity, this feature was not available for the elasticity. A summary statement about settings flashed at run time, indicating that the elasticity was set to 0.5, meaning nonconservation of kinetic energy, would likely have helped these students realize what they were doing. Explicit directions about setting the elasticity are not enough. At a minimum, students should be required to record all relevant settings deliberately in some fashion, even those whose relevance is not apparent to them.

Finally, the more precise, quantitative nature of the feedback did not lend itself to the development of robust theories-in-action because it did not necessarily correlate with explanations that would resonate with learners. The extensive affordances of the computer simulation with regard to parameter manipulation and read-out did permit the group to develop one theory that would not have been possible with the physical manipulatives. With the enhanced feedback, the group was able to identify a pattern for the ratio of velocities after the collision; however, they never developed an explanation for the phenomenon in the way that they were able to with the physical manipulatives, where they could ‘‘see’’ the objects exchanging momenta. The enhanced feedback did not lead to interpretation. Thus, the group was not able to leverage the additional information productively toward generating and enacting a plan for exploration of what happens in collisions, as they were able to do in the physical experiments.

This implies a need for further study in the interaction between the cognitive process of exploration and the exploration environment. Should experimentation be situated first in physical experiments, rooted in common experience, and then moved to a simulation environment as was the case with the group we studied here? A limitation of this study is that we cannot say with certainty how the order of the exploration, physical before simulated, affected the outcome.

(3) How does the learner context (prior experiences and beliefs) interact with prospective secondary science teachers' development and evaluation of theories-in-action? Does this interaction have implications for the design of open-ended learning environments?

The experiences and beliefs that these prospective teachers brought with them clearly affected their use of both the physical and simulated environments to develop theories-in-action about collisions. Land and Hannafin (1996) emphasized the role of a lack of formal domain knowledge as part of the learner context. Here, contrary to what one might expect, we found that prior *formal* knowledge in physics appeared to limit these students' ability to construct phenomena and test them systematically. Laura's authoritarian view of science, and her belief that her role as the expert was to ensure that others dismissed unproductive or limited theories in favor of accepted versions, acted to curb the exploration process even when the group was successful in making discoveries. The availability of the simulation actually supported her in this tendency because she was able to dismiss findings with the physical manipulatives that she viewed as unproductive by simply stating that the experiments would be better done in the ‘‘ideal system.’’ The computer might have aided Hal and Susan in defending their exchange theory, but difficulty in setting up the simulation precluded this.

This implies that scaffolding of the exploration process, whether in simulated or physical environments, should be a part of preservice training as well as classroom practice. In alignment with the assertion that simulations are most valuable when students use them to test their *own* conceptions (Gorsky & Finegold, 1992), it is particularly important that teachers, in their role as expert and guide, not act in ways that curb exploration. Requiring the group to present its evidence and justification for dismissing a finding, as well as having them state explicitly the conditions under which that finding held true, might have ensured validation for the theories-in-action that originated with the group. It would be possible to design such a scaffolding feature into a simulation program. For example, the program might require users to state the result of each simulation run along with interpretations and implications for the theory to be evaluated.

We also found that viewing the computer as a source of authority resulted in problems when it did not live up to student expectations. Like some of the students described by Steinberg (2000), Susan expected the computer to be an infallible source of authority. When it ‘‘betrayed her,’’ she vowed never to use it in her classroom. This finding also has implications for the design of open-ended learning environments, and their best use in classrooms. At best, the simulation should be able to recreate well-known limiting cases. At a minimum, teachers should take time to review the mechanisms behind the simulation, and discuss its benefits and limitations with students in advance. This might also imply that best practices would include use of physical manipulatives first, to motivate the need for the affordances of the simulated environment, and promote acceptance of its limitations.

Appendix

Interactive Physics™ predicts the outcomes of collisions using two constraints, conservation of energy and conservation of momentum. If the two colliding objects can be considered an isolated system (i.e., there are no effects from Earth's gravity, air or surface friction, etc.), and their gravitational and electromagnetic interactions are neglected, these two constraints take on the form of Equation (1) and Equation (2), respectively, for an elastic collision between Object A and Object B:

$$\tfrac{1}{2}m_A v_{A0}^2 + \tfrac{1}{2}m_B v_{B0}^2 = \tfrac{1}{2}m_A v_A^2 + \tfrac{1}{2}m_B v_B^2 \tag{1}$$

$$m_A v_{A0} + m_B v_{B0} = m_A v_A + m_B v_B \tag{2}$$

where m_A is the mass of object A, m_B is the mass of Object B, v_{A0} is the velocity of Object A before the collision, v_{B0} is the velocity of Object B before the collision, v_A is the velocity of Object A after the collision, and v_B is the velocity of Object B after the collision.

Multiplying Equation (1) by 2, rearranging, and factoring yields:

$$m_A(v_{A0} + v_A)(v_{A0} - v_A) = m_B(v_B + v_{B0})(v_B - v_{B0}) \tag{3}$$

Rearranging Equation (2) yields:

$$m_A v_{A0} - m_A v_A = m_B v_B - m_B v_{B0} \tag{4}$$

Dividing Equation (3) by Equation (4), and rearranging, yields the familiar rule that the approach velocity must equal the recession velocity in an elastic collision:

$$v_{A0} - v_{B0} = v_B - v_A \tag{5}$$

In collisions in which some of the kinetic energy is converted into another form, the elasticity, ε, is the fraction of kinetic energy remaining after the collision:

$$\varepsilon\left(\tfrac{1}{2}m_A v_{A0}^2 + \tfrac{1}{2}m_B v_{B0}^2\right) = \tfrac{1}{2}m_A v_A^2 + \tfrac{1}{2}m_B v_B^2 \tag{6}$$

Combining Equation (6) with Equation (2) yields an alternate definition of the elasticity:

$$\varepsilon = \frac{(v_B - v_A)}{(v_{A0} - v_{B0})} \tag{7}$$

The velocity of recession is simply the approach velocity multiplied by ε. In completely inelastic collisions, $\varepsilon = 0$, the objects stick together and v_B and v_A are equal. Interactive Physics solves Equation (2) and Equation (7) (with ε set to the lower of the two elasticities entered by the user) simultaneously to determine the values of v_A and v_B. If C is the ratio of m_B to m_A, then the solution for the ratio of v_B to v_A (the subject of the "ratio of velocities" theory-in-action developed by the group studied here) is:

$$\frac{v_B}{v_A} = \frac{v_{A0}(1+\varepsilon) + v_{B0}(C-\varepsilon)}{v_{A0}(1-C\varepsilon) + v_{B0}(C+C\varepsilon)} \tag{8}$$

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