Running head: MODEL DEVELOPMENT: FORMALIZING PRECONCEPTIONS

Facilitating Model Development Through Simulation:

Formalizing Student Preconceptions Into Physical Laws

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Abstract

Student preconceptions about force and motion are typically contextualized (tied to specific situations and scenarios) unlike the classic, general purpose laws taught in physics. However, constructivist pedagogy should make use of these preconceptions, developing them into (rather than replacing them with) accepted models. The ThinkerTools force and motion simulation software was augmented to add a “Model Design” feature, allowing it to simulate common non-Newtonian ideas about the behavior of objects. Christina Schwarz (1998) built a model-centric force and motion curriculum around this new version of the simulation software, and tried it out in several middle school classrooms. The results of this trial guided a redesign of the Model Design feature, recharacterizing its alternative law options to reduce contextualization and increase the focus on mechanism and causality. Interviews were then conducted with a small group of sixth grade students to determine whether the contextualized preconceptions they brought with them to the classroom could still guide them as they chose from this new set of alternate physical laws. Once each student had developed a complete model of force and motion, they were able to conduct microworld experiments based on that model to determine whether the objects in the simulation behaved as they would expect real objects to, and whether the experimental results agreed with their contextualized predictions. Where there was disagreement, the students revisited both their predictions and their law choices to resolve the discrepancies. The results suggest that students were able to make use of their preconceptions in evaluating physical laws, even though these preconceptions were highly contextualized and lacked consistency. A few students demonstrated exciting conceptual progress toward understanding both modeling and physics despite the brevity of the interviews.

Introduction

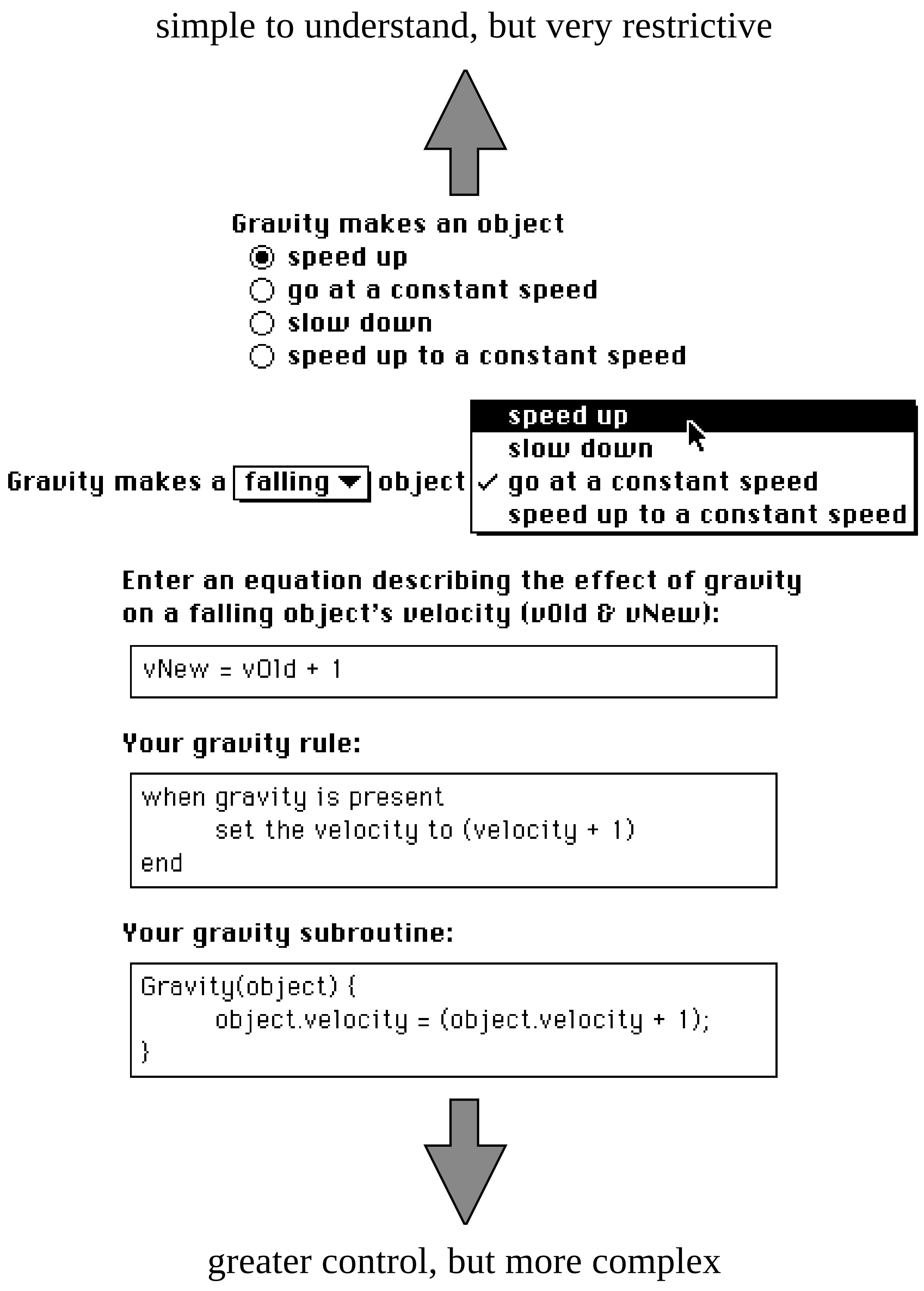
The ThinkerTools curriculum developed by Barbara White (1993b) makes use of simulation software to teach scientific inquiry and elementary mechanics to middle school students. The software facilitates conceptual change by simulating increasingly sophisticated microworlds, while maintaining a level of abstraction sufficient for the development of knowledge structures that can be transferred to new domains (White, 1993a). The curriculum is built around the Inquiry Cycle (White & Frederiksen, 1994), a framework that organizes student research work into phases (see Figure 1). After conducting both simulated and real world experiments, and then collecting and analyzing their data, students construct and evaluate scientific models to explain their results. The modeling phase of the curriculum has always been the most challenging for ThinkerTools students, because middle school students commonly have little experience articulating their own ideas about natural processes. They also have a very limited understanding of what the modeling process is all about.

Figure 1. ThinkerTools inquiry cycle.

To address this problem and to learn more about how students integrate scientific models, Christina Schwarz (1998) designed a special "model-centric" version of the ThinkerTools curriculum. Her Model Design curriculum focused on the general features of all models, the development and utility of scientific models, and the specific physical models physicists use to describe and predict behavior in classical mechanics. To support her research, I agreed to introduce features into the ThinkerTools simulation software that would allow students to experiment with alternate physical laws (e.g., "An impulse will cause a heavier mass object to travel faster than a lighter mass object."). The ThinkerTools software can simulate a wide range of physical phenomena, including one and two dimensional motion with or without sliding friction, fluid resistance, constant external gravitational fields of the form found near the surface of the earth, gravitational attraction between simulation objects, application of impulses (external forces applied over a short period of time) to simulation objects, as well as the effect of an object's mass on all of these phenomena. The simulation software code is based on the physical laws which govern these phenomena, so to implement alternate physical laws we had to divide the domain of the simulation into subdomains, one for each physical law. The full set of laws (effect of sliding friction on speed, mass and the effect of a force, mass and the force of gravity, etc.), would form a complete model of force and motion, which could then be used to conduct computer-based experiments. Through this process, students would hopefully come to better understanding of the relationship between a scientific model and the behavior it predicts or explains, and therefore be in a better position to construct, evaluate, and integrate scientific models.

Model Design Feature

As our team (Christina Schwarz, Barbara White, John Frederiksen, and myself) began to develop the interface for the new feature, we weren't sure what level of control would be most appropriate for our model designers. As constructivists, we wanted to give them tools for representing their own ideas about force and motion, which tend to differ dramatically from the accepted view of Newtonian mechanics (Clement, 1982; diSessa, 1983; diSessa, 1988; Elby, 1998; McCloskey, 1983a, 1983b; McDermott, 1984; Stavy, 1990). Indeed, research has demonstrated the effectiveness of curricula that confront or otherwise make use of these preconceptions (Clement, 1989; Elby, 1998; McDermott, 1984; Smith, diSessa, & Roschelle, 1993). Other researchers have suggested that encouraging learners to make their rules and reasoning structures explicit during problem solving helps both to integrate new ideas and transfer them to new domains (Brown, 1984; Gagné & Smith, 1962; Wilder & Harvey, 1971). The question was how to best capture a student's preconceptions so that they could control the simulation. Some researchers believe that students are employing self-consistent alternate “theories” of mechanics (McCloskey, 1983a, 1983b), while others contend that the preconceptions students bring with them to the classroom are fragmented, tied to specific contexts, and inconsistent (diSessa, 1983; diSessa, 1988; Elby, 1998; Stavy, 1990). Furthermore, as students commonly have trouble articulating their own ideas about force and motion, it was obviously going to be very difficult for a piece of software to translate those ideas into terms formal enough to control ThinkerTools simulations. We considered a continuum of possibilities ranging from simple multiple choice selections to computer code (see Figure 2).



Gravity makes an object
● speed up
○ go at a constant speed
○ slow down
○ speed up to a constant speed

Gravity makes a falling object

Enter an equation describing the effect of gravity on a falling object's velocity (vOld & vNew):

```
vNew = vOld + 1
```

Your gravity rule:

```
when gravity is present
      set the velocity to (velocity + 1)
end
```

Your gravity subroutine:

```
Gravity(object) {
      object.velocity = (object.velocity + 1);
}
```

Figure 2. Continuum of rule specification methods.

In order to make the software interface as simple for students as possible, we decided to begin our implementation at the least challenging end of this continuum. Given the multiple levels of knowledge we were expecting the students to develop simultaneously through the Model Design curriculum (principles of mechanics, scientific inquiry skills, utility of scientific models, modeling process, ThinkerTools experiment construction, etc.), trying to teach them computer programming as well would probably have extended the curriculum well beyond the time period available. It should be noted, however, that other researchers have been successful at using simulation software development as pedagogy for developing students’ understanding of force and motion (Adams & diSessa, 1991). Although multiple choice selections are perhaps the least authentic method of capturing preconceptions, we hoped that if the options we provided were based on the kinds of models commonly described by previous ThinkerTools students, most of our model designers would find options matching their understanding of force and motion.

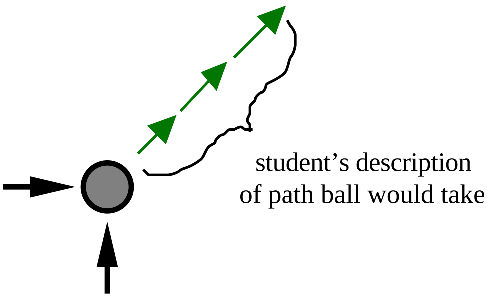
Given the constraint of a multiple-choice Model Design interface, White and Schwarz set about the task of identifying the most important physical laws covered in the ThinkerTools curriculum and developing an appropriate set of options for each. In addition to reviewing the literature on common student misconceptions, both researchers drew on their classroom observations and videotapes of 7th and 8th grade students discussing ThinkerTools predictive questions (see Figure 3). White and Schwarz also interviewed students at the end of the spring ’94 term to narrow in on some of these common theories. Finally, the researchers studied the justifications students gave for their answers to multiple-choice questions on the physics pretests administered during the spring ’94, fall ’94, and spring ’95 terms (see Figure 4). The alternate laws that emerged from this analysis had several overlapping attributes that made their implementation particularly challenging: 1) the laws were framed within contexts, 2) they described overall behavior rather than underlying mechanism, and 3) the interactions between laws were left unspecified. The following sections describe how we addressed these problems in the initial version of the software.

Coming up with Hypotheses

Predictive Question 1.

Imagine a ball on a frictionless surface. Suppose that the ball is stopped and that two people hit the ball at the same time. They both hit the ball with the same sized hits and apply their hits at right angles to one another.

What do you predict will happen? Show the path of the ball.



Why would that happen? *because when the two hits are applied*
the ball will slip out between the two bonkers and go off
diagonally

Would the ball go at the same speed as when only one person applies a hit, or would it go slower or faster? Explain your reasoning.

it'll go faster, from twice the force and a fricionless surface

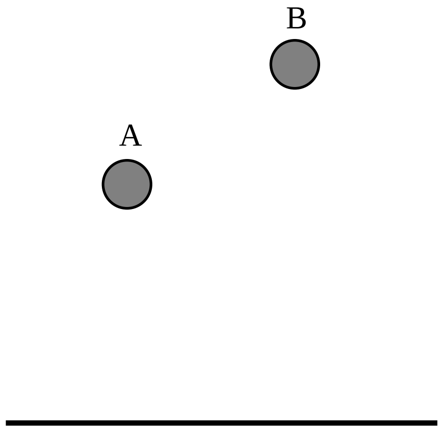
If you think that it goes faster or slower, how much (twice or just a little)?

it'll go a little faster

Figure 3. ThinkerTools predictive question.

Question 1

Imagine that you drop two identical balls from different heights. Both balls are dropped at exactly the same time.



Which ball hits the floor first? (circle your choice below)

[✓ (A)] The lower ball.
(B) The higher ball.
(C) Both balls hit the floor at the same time.

Explain the reasons for your choice: it has less distance to go

Which ball is going faster when it hits the floor? (circle your choice below)

(A) The lower ball.
[✓ (B)] The higher ball.
(C) Both balls are going the same speed with they hit the floor.

Explain the reasons for your choice: it has more time to ecxellerate

Figure 4. ThinkerTools physics pretest question.

Contextual Dependency of Student Models

Piaget (1970) theorized that young children have a hard time learning, manipulating, and applying abstract concepts. Until they have reached what he termed the “formal operational” stage, Piagetian theory suggests that they are only able to reason effectively within fairly concrete domains. However, Papert’s (1980) success teaching young children to write LOGO programs suggests that young minds are indeed capable of comprehending the abstract, given appropriate curricular scaffolds. White (1993a) suggests the use of causal models at an intermediate level of abstraction to bridge the gap between the concrete and the abstract. Whether the Piagetian developmental point of view is valid or not, it seems reasonable to assume that concrete domains are more comfortable places for minds of all ages. It is rare for an adult to engage in abstract discussion without resorting to examples. As we choose increasingly abstract domains, the clarity of argument depends more and more heavily on the tools of metaphor, analogy, and to a large extent, concrete examples. Thus, context not only inserts itself into our most abstract discussions, it is through context that humans (whatever their age) reason within these abstract domains and ultimately reach abstract conclusions.

Though now specified in more precise scientific language, the initial Model Design options developed by White and Schwarz (see Table 1) also had contextual dependencies. As the software developer, I naturally concentrated on how to implement these new force and motion laws via modifications to the ThinkerTools simulation engine. Our collaborations during this initial design phase soon fell into a pattern that continued throughout the development process: 1) the behavior of imaginary simulation objects would be described within a given scenario, 2) I would try to come up with ideas for how to implement this behavior, and so 3) I would recharacterize the model in more mechanistic[1] terms. 4) This would invariably lead to requests to further clarify the model, some of which could not be satisfied solely from the limited information in the students' descriptions. For example, some students apparently think that gravity causes objects to fall at a constant speed after they are dropped. Implementing an object moving at a constant speed is easy. The tough part is deciding exactly when the object should begin moving at this speed, or put another way: what is the precise set of events that constitute dropping an object? We eventually decided that any object not moving with respect to the gravitational field and not in contact with some other structure had just been "dropped," and would therefore immediately have an instantaneous velocity change in the direction of the gravitational field. Note that the student model descriptions on which we based this Model Design option included nothing about what happens to an object moving against and/or at right angles to the gravitational field. However, in order to specify the behavior of all possible ThinkerTools experiments, we were forced to extrapolate the student's contextualized model description into a general principle.

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[1] I use the term "mechanistic" in this paper to mean the ability of some physical law descriptions to clearly specify how the overall behavior of an entire class of systems might be simulated using a few general principles. By this definition, the law "gravity adds a little bit every second to the speed of a falling object" is more mechanistic than "an object dropped from a greater height will hit the ground at a higher speed."

Motion of objects when a continuous force (like gravity) is applied to a stationary or upwardly moving object:

I. Effect of gravity on the object's <u>speed</u>:

A. **Speeds up in the negative direction**. A continuous force (like gravity) will cause the object in motion to increase it's speed in the negative direction. This means that if it is tossed upwards, the object will slow down and eventually fall back downward.

1. **At a regular/constant rate**. (velocity increases in the negative direction by X cm/sec each time OR the distance between dotprints increases in the negative direction by X each time)

2. **Exponentially**. Gravity gets stronger closer to the earth's core. Because gravity gets stronger, it pulls harder and harder, the closer it gets to the ground.

3. **Without a regular pattern**. Gravity causes objects to fall down eventually, but there isn't any real pattern to the object's speed. It just falls.

B. **Falls fast/No momentum**. A continuous force (like gravity) will cause the object in motion to fall at a steady rate. If it tossed upward initially, gravity will overtake this motion so that it turns around and starts to fall.

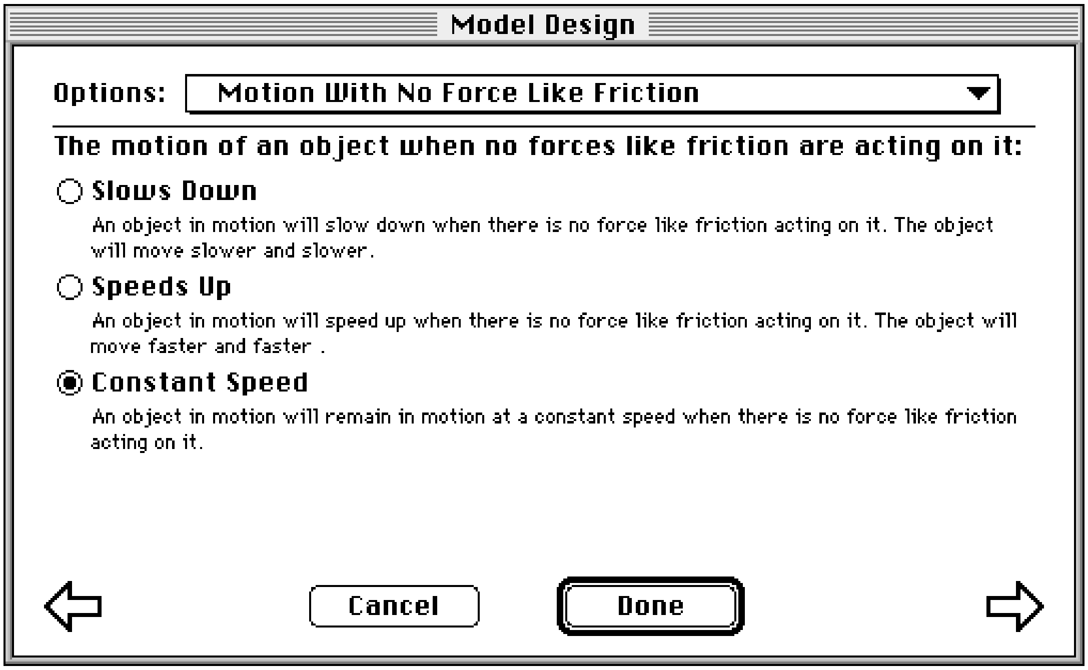
II. Effect of gravity on object's <u>direction of motion</u>: NEEDED?

A. **Downward**. Gravity pulls objects towards the surface of the earth. Even if an object begins traveling upwards because of a toss, gravity's pulls will eventually cause the object to start to fall downwards again.

B. **Down**. Gravity always pulls the object down, no matter how they start.

<u>Table 1.</u> Initial specifications for gravity and velocity options.

Another example of these complex scoping issues arose when we considered what should happen to a moving object in the absence of external forces. Most students believe that moving objects naturally slow down, even when there are no forces like friction present. This preconception is understandable, given the fact that friction exerts a significant force on every object that moves through our environment. However, students aren't normally able to see that friction is the underlying cause for this familiar behavior, especially in relatively low friction contexts such as coasting along on a bicycle. In order to implement this preconception, we added a set of Model Design options for the motion of an object when no forces are acting on it. The question was whether the option chosen should apply to environments that did contain friction (or other forces). Here we decided that the rule was much easier to understand in context, rather than specified more abstractly (e.g., “motion with or without friction”), so we worded the options to make the limited scope clear (see Figure 5).



Options: Motion With No Force Like Friction

The motion of an object when no forces like friction are acting on it:

○ Slows Down
An object in motion will slow down when there is no force like friction acting on it. The object will move slower and slower.

○ Speeds Up
An object in motion will speed up when there is no force like friction acting on it. The object will move faster and faster .

● Constant Speed
An object in motion will remain in motion at a constant speed when there is no force like friction acting on it.

Figure 5. Model design options for motion with no force like friction[2] .

It’s interesting to note that this process of rigorous behavior specification is in fact the lion’s share of any software development effort. For example, when a user requests a new feature for an existing piece of software, their description will invariably be tied to a particular usage scenario. When the development team evaluates such a request, they are usually in a much better position to envision the most appropriate method of addressing the issue. Any seasoned team, though, recognizes the importance of building screen shots and/or mockups, for the act of interface specification usually raises issues not considered within the original user’s context. The true test,

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[2] Unless otherwise noted, all Model Design screens are displayed with the accepted Newtonian option chosen.

however, comes when the engineer begins to implement the new feature, because only through the implementation can the true behavior across all contexts be envisioned (if then). A second analogy can be drawn between the development of the Model Design feature and the development of an expert system[3] . To build such a system, the engineer interviews experts in the domain and then tries to construct an organized knowledge framework from their responses. Within the domains most amenable to expert systems, the experts' knowledge may at first glance seem to be a simple set of highly contextualized if-then rules. However, though an expert may resort to context in order to describe the target behavior, his or her internal knowledge representation is actually much more general than that, for human experts are typically able to apply their knowledge to new contexts. The shared goal of the expert and expert systems engineer is to specify this knowledge in abstract form, so that it can be applied across as many contexts as possible. Software development can thus be seen as the abstraction of information and mechanism from more concrete ideas about the desired behavior of a system in context, just as physics is the abstraction of physical laws from the results of experiment.

Inferring Mechanism from Contextualized Behavior

In addition to being highly contextualized, the preconceptions of our ThinkerTools students had a behavioristic character, as the students were understandably more comfortable explaining what would happen (i.e., empirical results) than why it might happen (i.e., causal models). In most cases, the students probably hadn't considered the underlying mechanistic or causal issues very deeply. However, we tried very hard to infer plausible causality arguments to unpack and explain these behavioral descriptions, for without a clear definition of the underlying mechanism

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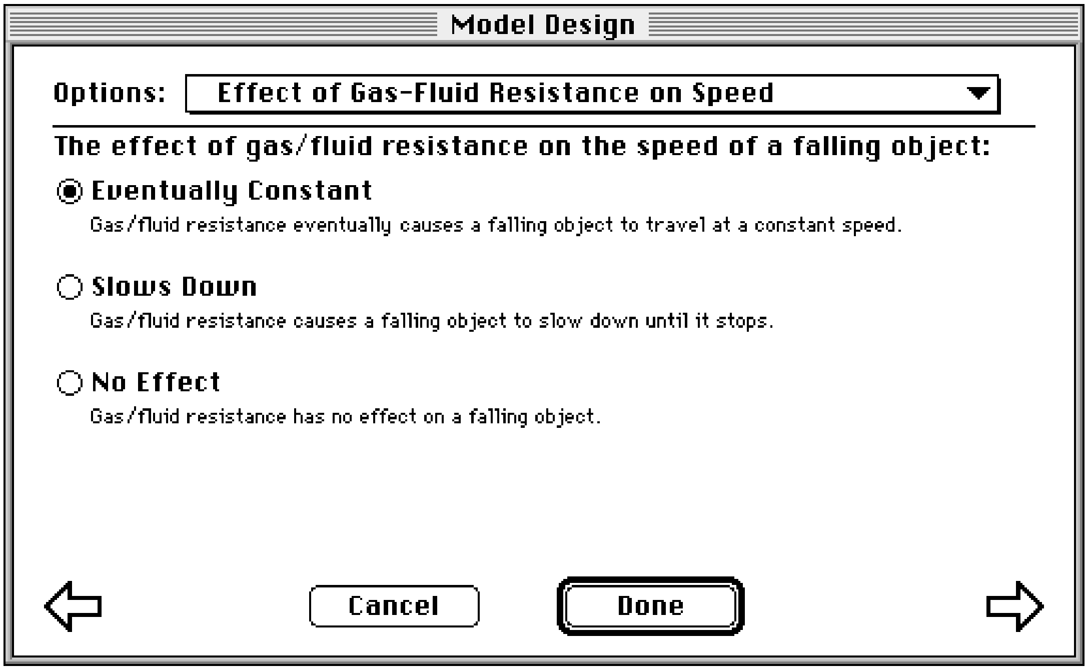
[3] An expert system is a piece of software that attempts to approximate the behavior of a human expert within a carefully constrained domain. One of the most famous early expert systems is MYCIN (Shortliffe, 1976), a program that automatically diagnoses blood diseases based on answers provided in response to its questions about patient symptoms.

(i.e., how different rules would combine to affect the position of an object on a timestep by timestep basis) we could not simulate the overall behavior described by the students. For example, students often correctly predict that the smoother a surface is, the farther an object will slide on it. However, this does not specify how the object's speed will change over time; it might decrease linearly, exponentially, or instantaneously.

Even when student models included some causality arguments, we still had to infer much of the underlying mechanism. For example, many students believe that gravity begins acting on an object thrown into the air only after the force applied by your hand "has worn out," and the object reaches top of its trajectory. Interpreting this explanation is no easy task. Is the force of gravity "wearing out" the velocity that the object gained from your hand's force (the Newtonian interpretation), or would your hand's force have "worn out" on its own just as quickly were gravity not present? We considered two general approaches for dealing with these issues. The first approach is to implement the student's description literally, no matter what behavior might result. Since the topic of gravity appears in the curriculum several weeks after the topic of motion independent of forces, the student should understand that forces don't wear out (Newton's First Law), and so would reason that only gravity could be responsible for the deceleration of objects moving upward as well as the acceleration of falling objects. Thus, the appropriate way to implement "gravity begins affecting an object thrown up only once it comes to a stop" is to let the object continue upward forever. The student is then forced to choose "gravity is always acting" in order to get behavior consistent with their experience. The danger, of course, is that the student will reject all of the Model Design options, since none of them both match their causal understanding and result in behavior that matches their experience. Even if the curriculum explicitly refers back to their conclusion that objects continue moving when no forces are present, it's reasonable for them to see the behavior of objects thrown into the air as evidence that Newton's First Law (on shaky ground to begin with) must be wrong. A more conservative approach to these issues is to restrict the scope of the Model Design option so that it was responsible only for the behavior of objects with the contexts most familiar to students and in which they're more comfortable reasoning. We decided that the overriding concern was that the behavior of the simulation should match the student's expectation as closely as possible within the context of their description. Thus, we decided to have objects thrown into the air behave in a Newtonian manner until they had come to a stop with respect to the gravitational field. Thus the Model Design option chosen by the student would only affect the behavior of falling objects.

The description above illustrates how the interaction between separate physical laws (e.g., behavior of moving objects independent of forces vs. behavior of objects in a gravitational field) can complicate the task of selecting the most appropriate Model Design option for a single physical law. We ran into a similar problem when trying to come up with appropriate options for the behavior of an object moving through a fluid (either a gas or a liquid). The most natural context in which to evaluate this behavior (and the easiest one to design physical experiments for) is the motion of an object falling through a fluid under the influence of gravity. Escaping the effects of gravity by studying a neutral buoyancy object moving horizontally under water seemed too far removed from the experience of the average 7th grade student to result in meaningful and far-reaching conclusions. We therefore concentrated on the (behavioristic) question of whether an object dropped into a fluid (i.e., possessing an initial velocity through the fluid in the direction of the gravitational field) would eventually come to rest (see Figure 6). The ThinkerTools software simulates friction and fluid resistance via a global switch that affects the entire simulation, and therefore is unable to simulate the boundary between a zero friction environment and a fluid-filled environment. The mechanism for slowing and stopping an object moving downward through a fluid was to simply pretend that there was no gravity field whatsoever. Thus, the “slows down until it stops” gas-fluid resistance Model Design option overrode whatever Model Design option had been selected for the effect of gravity. In this case, though the behavior might be consistent with a student’s prediction, the mechanism was arbitrary.



Options: Effect of Gas-Fluid Resistance on Speed

The effect of gas/fluid resistance on the speed of a falling object:

● Eventually Constant
Gas/fluid resistance eventually causes a falling object to travel at a constant speed.

○ Slows Down
Gas/fluid resistance causes a falling object to slow down until it stops.

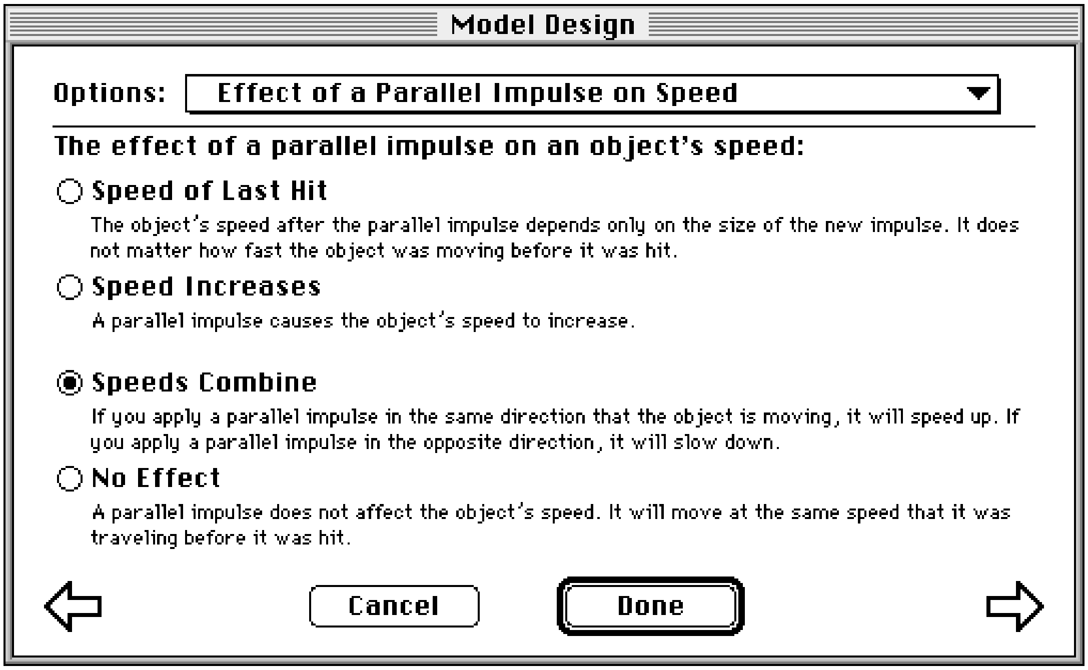
○ No Effect
Gas/fluid resistance has no effect on a falling object.

Figure 6. Model design options for the effect of fluid resistance on speed.

Context Divisions

The Newtonian explanation for the effect of an arbitrary impulse on a moving object is deceptively simple. The impulse produces a change in velocity which is combined with the original velocity by vector addition. Taking the confusing mechanics of vector addition aside, it’s surprising that a single law could explain the behavior of an object receiving an impulse when at rest, an object receiving an impulse in the same direction as its velocity, an object receiving a small impulse opposite its high velocity, an object receiving a large impulse opposite its small velocity, and an object receiving an impulse at right angles to its velocity. Student descriptions of their models suggest that they believe separate laws should be applied to these different situations, and the subject is sufficiently complicated that one-dimensional motion is normally covered separately in the standard ThinkerTools curriculum (as well as high school and college physics curricula). The natural approach seemed to be to divide this area of the Model Design into two contexts, one for the effect of an impulse parallel to the object's current velocity and the other for the effect of a perpendicular impulse. Each context had its own set of Model Design options. It was hoped that by carefully wording the Newtonian options for each context, the similarity between the two could be appreciated, and as a final step in their analysis the students could perhaps discover (or be shown) how all of the laws could be expressed in a single statement.

The second problem we faced in trying to implement student models for the effect of an impulse was the sheer number of possible alternatives. Some students focused on the direction that the object would be moving after the impulse, while others described the change in the object's speed. In order to encourage students to pay attention to both features of the result, we decided to divide the Model Design options again so that they could consider these effects separately. This last change introduced a consistency problem for the parallel impulse context, since the Newtonian option for the speed effect included implications for the direction effect (see Figure 7), and the Newtonian option for the direction effect included implications for the speed effect (see Figure 8). It simply was not possible to specify a reasonably complete Newtonian description of the change in an object's speed due to a parallel impulse without implying something about the direction as well. Thus, specifying a Newtonian speed option contradicted all non-Newtonian direction options (and vice-versa). In this case, we decided to have the simulation inform the students about the contradiction and advise them to change one of the two selections (see Figure 9). Note that such contradictions were impossible between the speed and direction options for perpendicular impulses (see Figures 10 and 11), since the linear independence of the two components (current velocity and impulse) allowed the Newtonian speed calculation to be performed without implying anything about the new direction (and vice-versa).



Model Design

Options: Effect of a Parallel Impulse on Speed

The effect of a parallel impulse on an object's speed:

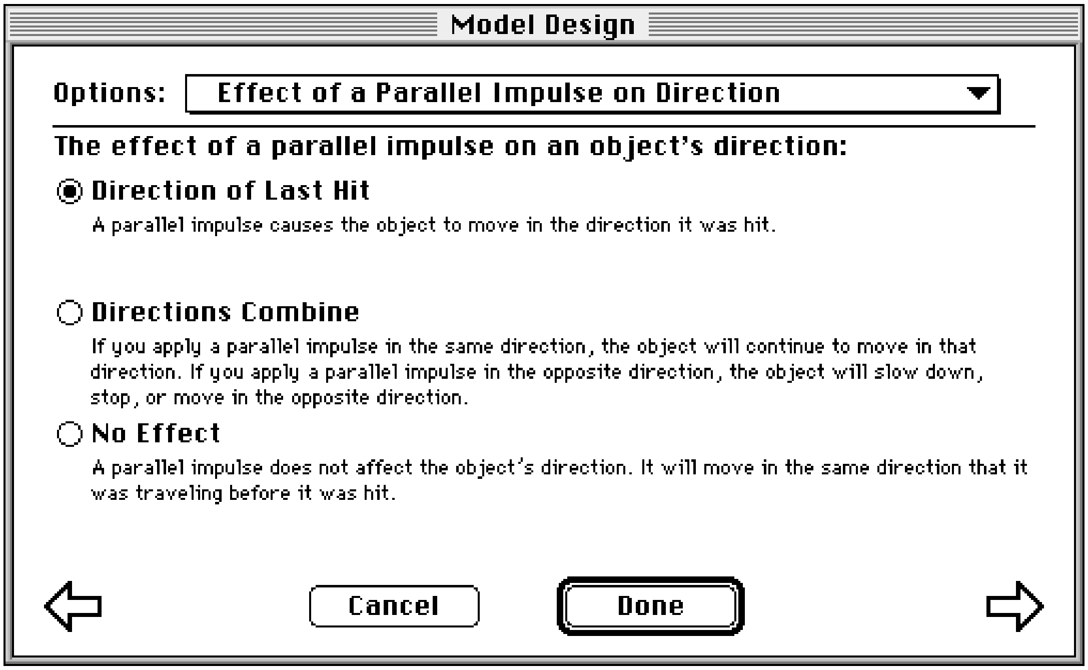
○ Speed of Last Hit
The object's speed after the parallel impulse depends only on the size of the new impulse. It does not matter how fast the object was moving before it was hit.

○ Speed Increases
A parallel impulse causes the object's speed to increase.

● Speeds Combine
If you apply a parallel impulse in the same direction that the object is moving, it will speed up. If you apply a parallel impulse in the opposite direction, it will slow down.

○ No Effect
A parallel impulse does not affect the object's speed. It will move at the same speed that it was traveling before it was hit.

Figure 7. Model design options for the effect of a parallel impulse on speed.



Options: Effect of a Parallel Impulse on Direction

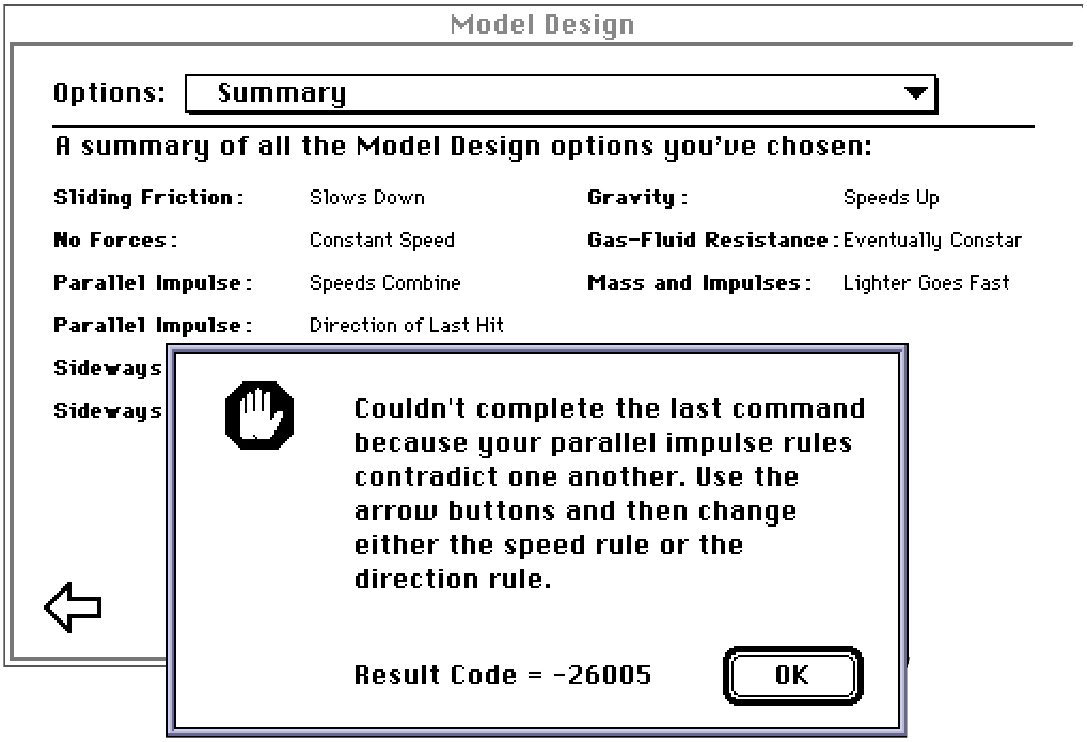
The effect of a parallel impulse on an object's direction:

● **Direction of Last Hit**
A parallel impulse causes the object to move in the direction it was hit.

○ **Directions Combine**
If you apply a parallel impulse in the same direction, the object will continue to move in that direction. If you apply a parallel impulse in the opposite direction, the object will slow down, stop, or move in the opposite direction.

○ **No Effect**
A parallel impulse does not affect the object's direction. It will move in the same direction that it was traveling before it was hit.

Figure 8. Model design options for the effect of a parallel impulse on direction (non-Newtonian option selected).



Options: Summary

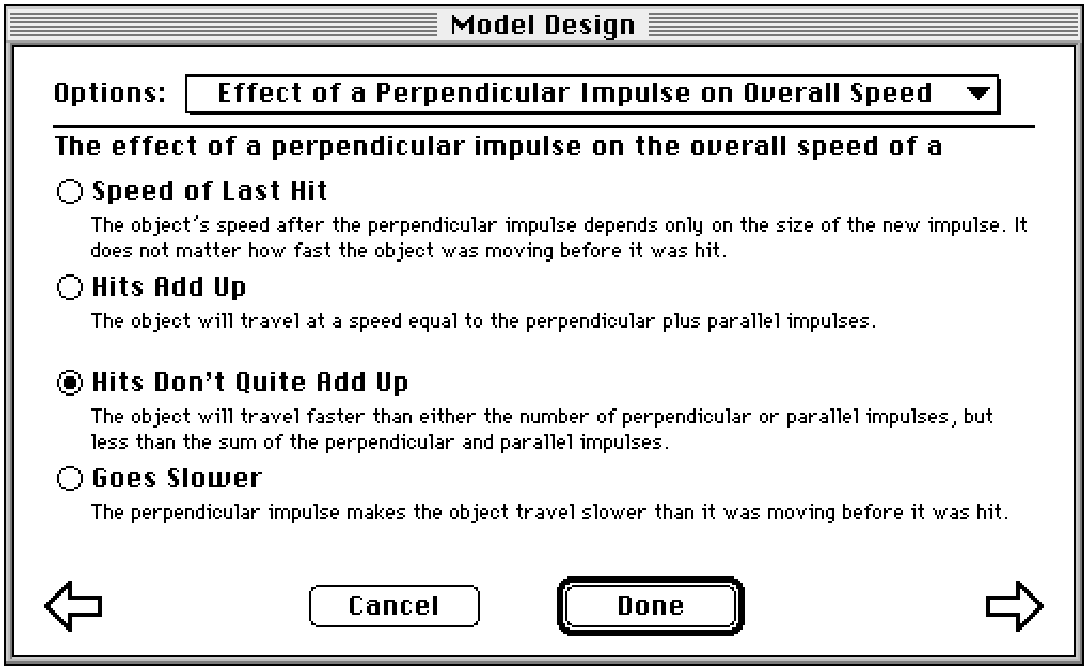
A summary of all the Model Design options you've chosen:

Sliding Friction:	Slows Down	**Gravity:**	Speeds Up
No Forces:	Constant Speed	**Gas-Fluid Resistance:**	Eventually Constar
Parallel Impulse:	Speeds Combine	**Mass and Impulses:**	Lighter Goes Fast
Parallel Impulse:	Direction of Last Hit		
Sideways			
Sideways			

Couldn't complete the last command because your parallel impulse rules contradict one another. Use the arrow buttons and then change either the speed rule or the direction rule.

Result Code = -26005

Figure 9. Reporting a conflict between parallel impulse laws.



Options: Effect of a Perpendicular Impulse on Overall Speed

The effect of a perpendicular impulse on the overall speed of a

○ **Speed of Last Hit**

The object's speed after the perpendicular impulse depends only on the size of the new impulse. It does not matter how fast the object was moving before it was hit.

○ **Hits Add Up**

The object will travel at a speed equal to the perpendicular plus parallel impulses.

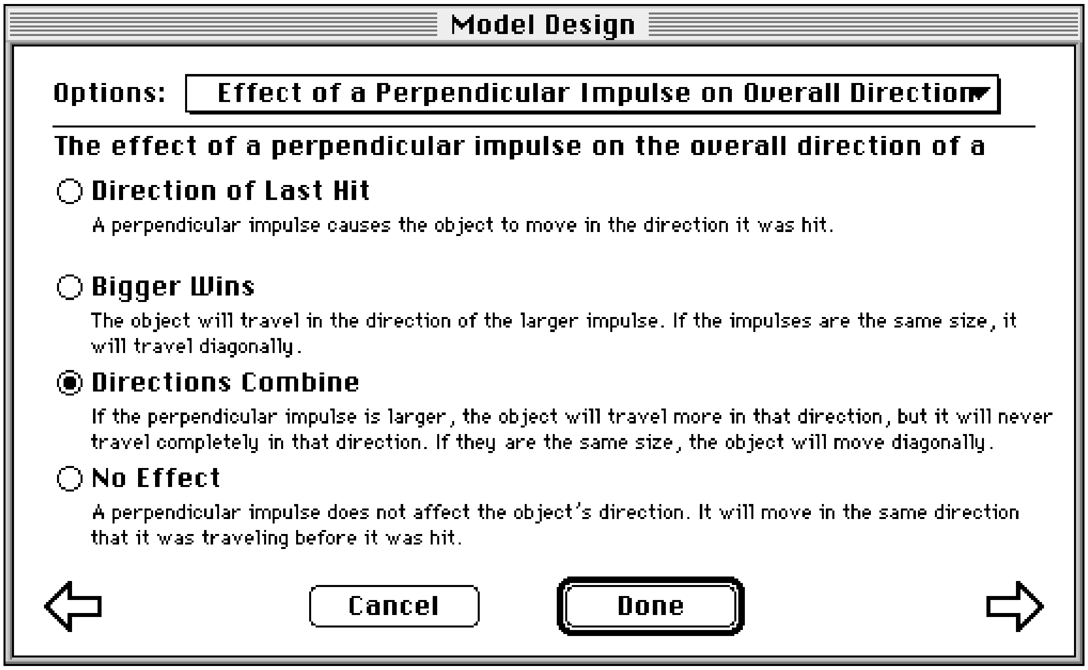
● **Hits Don't Quite Add Up**

The object will travel faster than either the number of perpendicular or parallel impulses, but less than the sum of the perpendicular and parallel impulses.

○ **Goes Slower**

The perpendicular impulse makes the object travel slower than it was moving before it was hit.

Figure 10. Model design options for the effect of a perpendicular impulse on speed.



Options: Effect of a Perpendicular Impulse on Overall Direction

The effect of a perpendicular impulse on the overall direction of a

○ **Direction of Last Hit**

A perpendicular impulse causes the object to move in the direction it was hit.

○ **Bigger Wins**

The object will travel in the direction of the larger impulse. If the impulses are the same size, it will travel diagonally.

● **Directions Combine**

If the perpendicular impulse is larger, the object will travel more in that direction, but it will never travel completely in that direction. If they are the same size, the object will move diagonally.

○ **No Effect**

A perpendicular impulse does not affect the object's direction. It will move in the same direction that it was traveling before it was hit.

Figure 11. Model design options for the effect of a perpendicular impulse on direction.

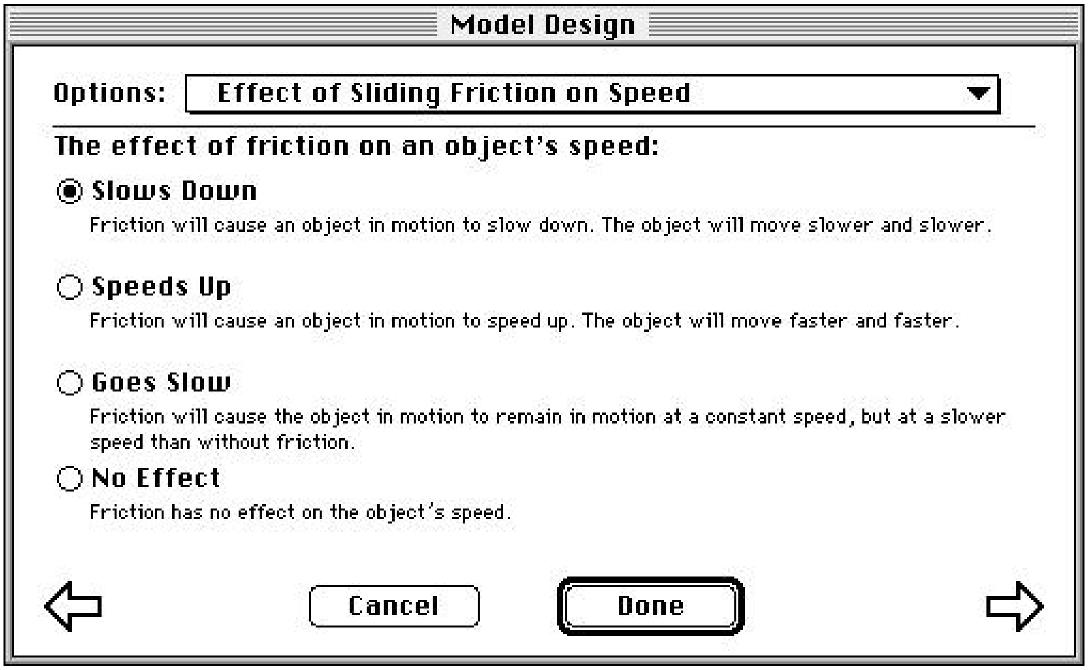
Results of the Model Design Curriculum

Schwarz (1998) taught her Model Design curriculum to four seventh grade classes over the fall ’96 term. The curriculum was divided into three scaffolded inquiry modules: 1) one dimensional motion with and without friction, 2) one dimensional motion with impulses, and 3) two dimensional motion with impulses, and then a choice from three independent projects: 1) gravity and velocity, 2) mass and the effect of an impulse, and 3) gas/fluid resistance. To investigate each module subdomain, her students followed the beginning of the normal ThinkerTools Inquiry Cycle (White, 1993b) of answering predictive questions, performing real world experiments, collecting and analyzing data, and building tentative models to explain their results. However, after this initial modeling phase, they evaluated the Model Design options for that subdomain, selected one, and then ran simulated ThinkerTools experiments based on their selections.

Her initial analysis of the student research book entries indicated that most students benefited from the additional opportunity to consider the physics by evaluating, discussing, and commenting on the Model Design options. However, there appeared to be attitude differences between high achieving and low achieving students. The low achieving students were quite interested in the relationship between the textual descriptions of the Model Design laws and the behavior of the ThinkerTools experiments; they enjoyed the control that the feature gave them over the simulation. In contrast, the high achieving students failed to see the point of the exercise. They thought that once a Model Design option was chosen there was little reason to run the simulation, as the results could easily be predicted from the description of the law. Although we were encouraged by the fact that most students were apparently able to appreciate the relationship between the Model Design options and the simulation behavior that resulted, this feedback suggested that there was room for us to shift to more mechanistic, less behavioristic law descriptions.

Review of Model Design Options

After this first run of the Model Design curriculum was complete, we convened the research group to review the Model Design feature, both on its own merits and in view of these results. The first observation made was that the contextualization of the Model Design laws meant that in some cases one law was forced to override another. For example, the Newtonian sliding friction option stated “Friction will cause an object in motion to slow down” (see Figure 12). This contradicted one of the gravity options, which stated “Gravity causes an object to fall at a constant speed” (see Figure 13). (Technically, the Newtonian sliding friction option contradicted all but one of the gravity options, but this was the clearest contradiction.) In a ThinkerTools simulation containing both friction and gravity, which law should prevail? The current implementation had the friction option defer to the constant speed gravity option, with the effect that adding friction to a simulation containing gravity would have no effect on the behavior of the object. The gravity-fluid resistance interaction mentioned earlier contributed to a general lack of satisfaction with the level of specification in the language of the Model Design options with regard to law interactions. Several solutions were suggested, the first of which was to add text to the law descriptions to make the interactions clearer. For example, “In the absence of other forces, friction will cause an object in motion to slow down.” Beyond the awkwardness of this language, the group had difficulty arriving at a consensus for which law should take precedence. This led to the idea of having the students specify law interactions explicitly. For example, when a contradicting laws were chosen, the Model Design software could ask the student which should take precedence (see Figure 14). This method had the disadvantage of complicating an already challenging law selection process by raising issues far from the context in which the student was reasoning (e.g., moving from thinking about objects sliding across a surface to objects sliding down an inclined plane). Gravity is not normally considered by the students until after they've mastered friction and impulses (so that they have a better understanding of how forces affect the motion of objects). Another method of resolving these contradictions would be to wait until a simulation containing the necessary environmental factors (e.g., both gravity and friction) was constructed, and then ask the student to resolve the conflict when that simulation was first run. However, the more we considered how laws could potentially combine (e.g., the effect of one law could be added to or used to scale the effect of another, rather than simply overriding it), the more complicated the specification seemed, especially given the limitations of using natural language (as opposed to programming language) to specify the laws. Furthermore, we wanted the specification of the Model Design options to lead the students away from a contextualized understanding of world toward a view based on more widely-applicable general principles. Specifying that one law should override another in a given context seemed to work against the notion of consistency so important to scientific models.



Options: Effect of Sliding Friction on Speed

The effect of friction on an object's speed:

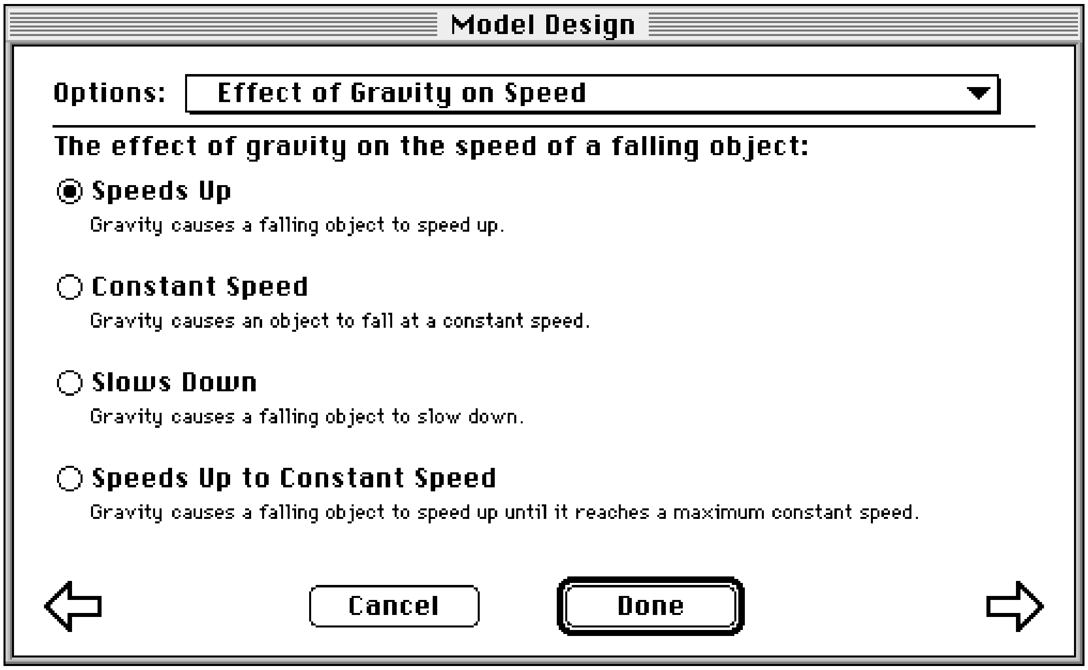
● Slows Down
Friction will cause an object in motion to slow down. The object will move slower and slower.

○ Speeds Up
Friction will cause an object in motion to speed up. The object will move faster and faster.

○ Goes Slow
Friction will cause the object in motion to remain in motion at a constant speed, but at a slower speed than without friction.

○ No Effect
Friction has no effect on the object's speed.

Figure 12. Model design options for the effect of sliding friction on speed.



Options: Effect of Gravity on Speed

The effect of gravity on the speed of a falling object:

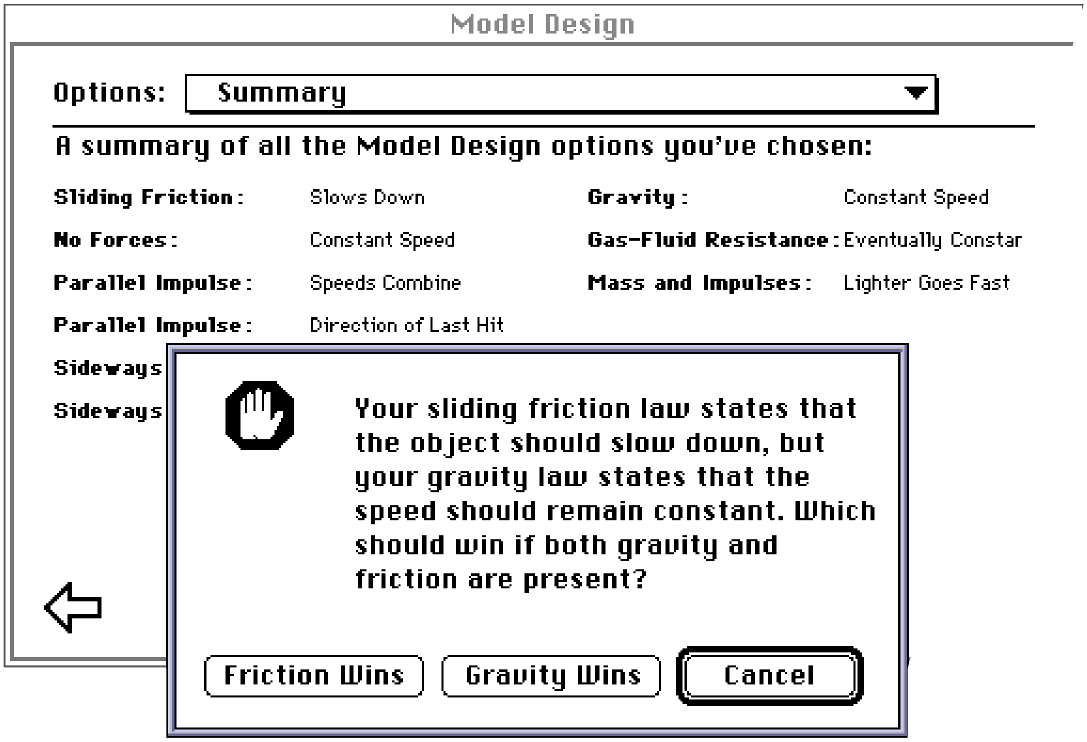
● Speeds Up
Gravity causes a falling object to speed up.

○ Constant Speed
Gravity causes an object to fall at a constant speed.

○ Slows Down
Gravity causes a falling object to slow down.

○ Speeds Up to Constant Speed
Gravity causes a falling object to speed up until it reaches a maximum constant speed.

Figure 13. Model design options for the effect of gravity on speed.



Options: Summary

A summary of all the Model Design options you've chosen:

Sliding Friction: Slows Down
No Forces: Constant Speed
Parallel Impulse: Speeds Combine
Parallel Impulse: Direction of Last Hit
Sideways
Sideways
Gravity: Constant Speed
Gas-Fluid Resistance: Eventually Constar
Mass and Impulses: Lighter Goes Fast

Your sliding friction law states that the object should slow down, but your gravity law states that the speed should remain constant. Which should win if both gravity and friction are present?

Figure 14. Asking the user to decide which law should take precedence.

Finding the appropriate level of contextualization proved to be the most controversial issue. Some of us thought that the current set of Model Design options were described in language that was too abstract for our students to fully appreciate. For example, forcing students to come up with a single law to describe the effect of an impulse on 1) a stopped object, 2) an object moving in direction of the impulse, and 3) an object moving in the opposite direction seemed too great a task if we really wanted to encourage them to make effective use of their highly contextualized preconceptions. To address this concern, it was suggested that we divide the Model Design subdomains further, so that students could choose from options that were more similar to their preconceptions. Others thought that the goal of the activity was to lead students from their contextualized preconceptions toward an appreciation for the greater power of more general laws. Contextualizing the description of our Model Design options (especially the Newtonian ones) seemed to be at best ineffective and at worst wholly counterproductive from the perspective of scaffolding the target behavior. After all, the goal of the Model Design curriculum was to teach kids how to construct scientific models that are useful for predicting and explaining the behavior of as many scenarios as possible, even those outside their familiar experience. To quote the noted physicist Richard P. Feynman (1963):

> The most dramatic moments in the development of physics are those in which great synthesis takes place, where phenomena which previously had appeared to be different are suddenly discovered to be but different aspects of the same thing. The history of physics is the history of such syntheses, and the basis of the success of physical science is mainly that we are *able* to synthesize.

A Shift Toward Mechanism

The root cause of the law interaction problem seemed to be an inappropriate focus on the external behavior of objects (i.e., the overall result), rather than the contribution of a law to a change in the behavior of an object. For example, the Newtonian option for sliding friction specified that the object would slow down. As mentioned before, this was certainly not the case if gravity was also pulling on the object. Our solution was to have each law specify a contribution to the overall behavior of the object, and to reword each law to describe the mechanism for this effect. Thus, we settled on rearchitecting the new Model Design feature around a law combination method analogous to the Newtonian method for combining forces: each of our laws would make a contribution to the behavior of an object, and these effects would then be summed together for the simulation result.

To support this new focus on mechanism, we had to make our implementation details more explicit in the specification of each law. However, the algebraic and vector calculations on which the simulation is based are certainly too abstract to be clearly understood by our model designers. A central part of the ThinkerTools curriculum is the idea of intermediate causal models that bridge the gap between empirical results and these abstract formalisms (White, 1993a, 1993b). For example, when students study the effect of a continuous force like gravity, the curriculum guides them to model the force as a series of small impulses spaced out through time (see Table 2). The concept of a simulation “timestep” is introduced early in the standard curriculum to support this kind of analysis. In the Model Design curriculum, students spend even more time focusing on timesteps, as one of the main goals of the curriculum is to understand exactly how the ThinkerTools software simulates the real world. Our idea was to make use of the timestep concept to shift the character of the Model Design feature so that instead of simply describing alternate empirical results, it became an environment in which these causal models became explicit enough to be evaluated by our students.

(2) Applying a Force to Get a Constantly Increasing Speed.

Now make the dot accelerate as it falls by making it go faster and faster.

Explain how you know the dot is accelerating.

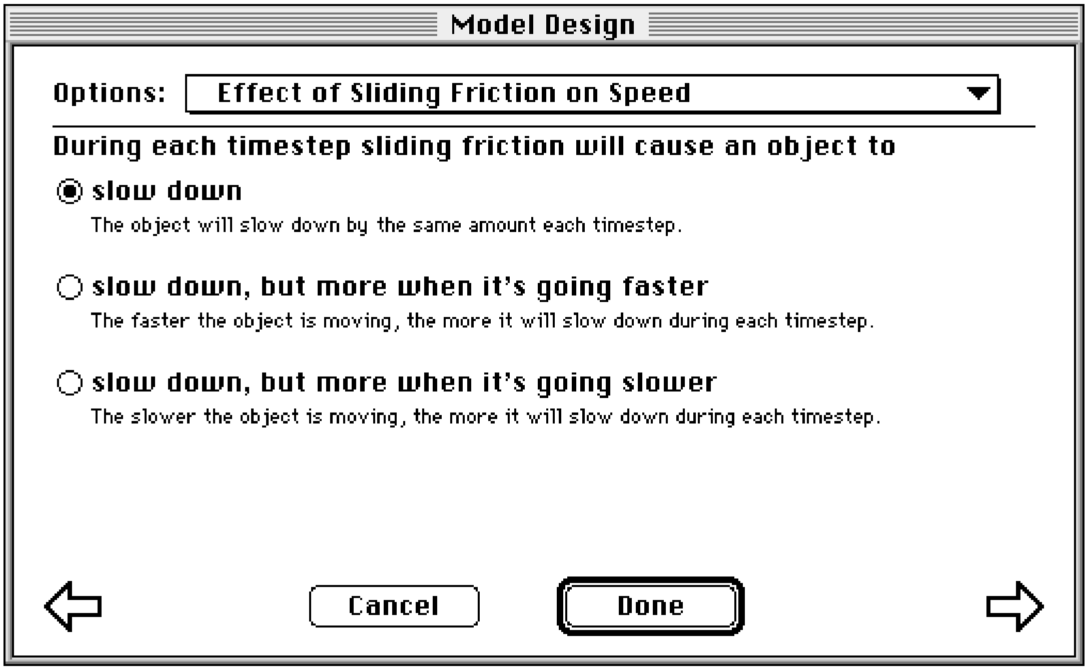
because the dot prints get farther and farther apart which shows its increasing speed

Describe how you got the dot to accelerate as it falls.

I kept applying impulses at a steady rate

Table 2. Modeling gravity via the application of impulses.

The new version of the sliding friction options were thus reworded so that instead of describing the overall behavior of an object moving through an environment containing sliding friction, they described what sliding friction did to an object’s motion during each timestep (see Figure 15). While shifting the Newtonian sliding friction option to a mechanistic focus was fairly straightforward (and perhaps subtle), we were unable to do the same for the “friction makes objects go slow” option (see Figure 12). This is not surprising, given the awkwardness of this law’s implementation (all changes in an object’s velocity due to forces were divided by a factor proportional to the amount of sliding friction present.) Although the implementation did result in constant motion that was slower than in environments with no sliding friction, it seemed ludicrous to try to describe this as the causal mechanism underlying friction. Our decision to shift to a mechanistic description thus forced us to abandon the “friction makes objects go slow” option completely. We also discarded the other non-Newtonian sliding friction options, replacing them with options that focused instead on how the size of the effect during a single timestep depended on the velocity of the object.



Model Design

Options: Effect of Sliding Friction on Speed

During each timestep sliding friction will cause an object to

● **slow down**
The object will slow down by the same amount each timestep.

○ **slow down, but more when it’s going faster**
The faster the object is moving, the more it will slow down during each timestep.

○ **slow down, but more when it’s going slower**
The slower the object is moving, the more it will slow down during each timestep.

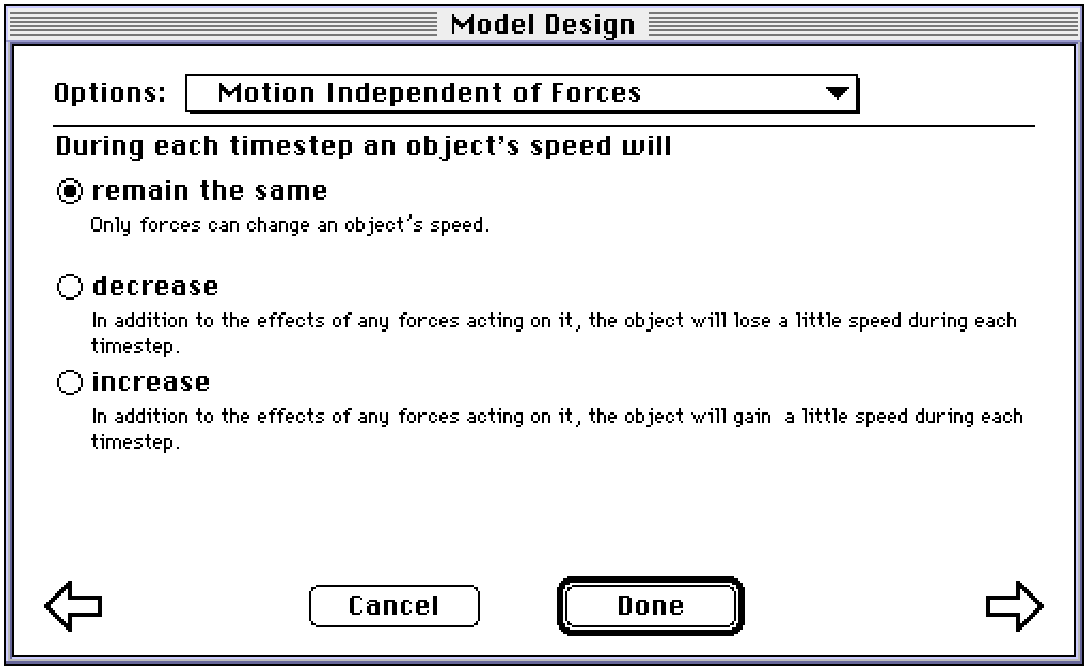
Figure 15. Revised model design options for the effect of sliding friction on speed.

This shift in character made another aspect of the Model Design feature much more straightforward. In order to help students understand how the laws they’ve chosen result in overall behavior, the simulation can be run in single-step mode, allowing a single one-second timestep to be simulated each time the user presses a special key. As the simulation applies each law, it uses the Macintosh Text to Speech Manager to audibly describe how the law is affecting the object’s motion. For example, this “Talking Model” feature (White & Frederiksen, 1990) causes the Newtonian no force law to state the following at the beginning of each timestep for each constantly moving simulation object: “Without a force like friction acting on me, I will stay the same speed.”

Finding appropriate text to be spoken at the beginning of each timestep is much easier and more natural if the law is specified mechanistically. For example, the original version of the Newtonian gas/fluid resistance law said “Gas/fluid resistance eventually makes me travel at a constant speed as I fall,” even before the forces became balanced (e.g., while the object was still decelerating after being dropped into the fluid). By shifting the law description to what happens during a timestep, these audible descriptions often made a lot more sense, “I’m moving fast, so gas/fluid resistance makes me slow down a lot.”

De-contextualization

The shift toward a more mechanistic view also settled the law scoping issue in favor of radical de-contextualization, resulting in broad changes to the set of Model Design options available. We began with the “motion with no force like friction” law, changing it to take effect even when other forces were present. The new law became “motion independent of forces,” (see Figure 16) and the option chosen by the student is now applied during every simulation timestep. De-contextualizing the laws governing the effect of impulses resulted in a dramatic simplification of the Model Design feature. Instead of four pages of options (supporting 112 valid combinations), we stripped this subdomain down to a single page containing the three most common student preconceptions about impulses (see Figure 17). Another advantage of the single impulse law was that it defined the result in one context not covered by the old method: the effect of an impulse that was neither parallel nor perpendicular to the object’s current velocity. We also de-contextualized the original “Mass and the Effect of an Impulse” law (see Figure 18) into a “Mass and the Effect of a Force” law, so that it would affect the behavior of objects under the influence of gravity as well (see Figure 19). Extracting the fluid resistance laws from the context of gravity was accomplished by focusing (as we did for the new sliding friction options) on how the size of the effect during a single timestep depended on the velocity of the object (see Figure 20).



Options: Motion Independent of Forces

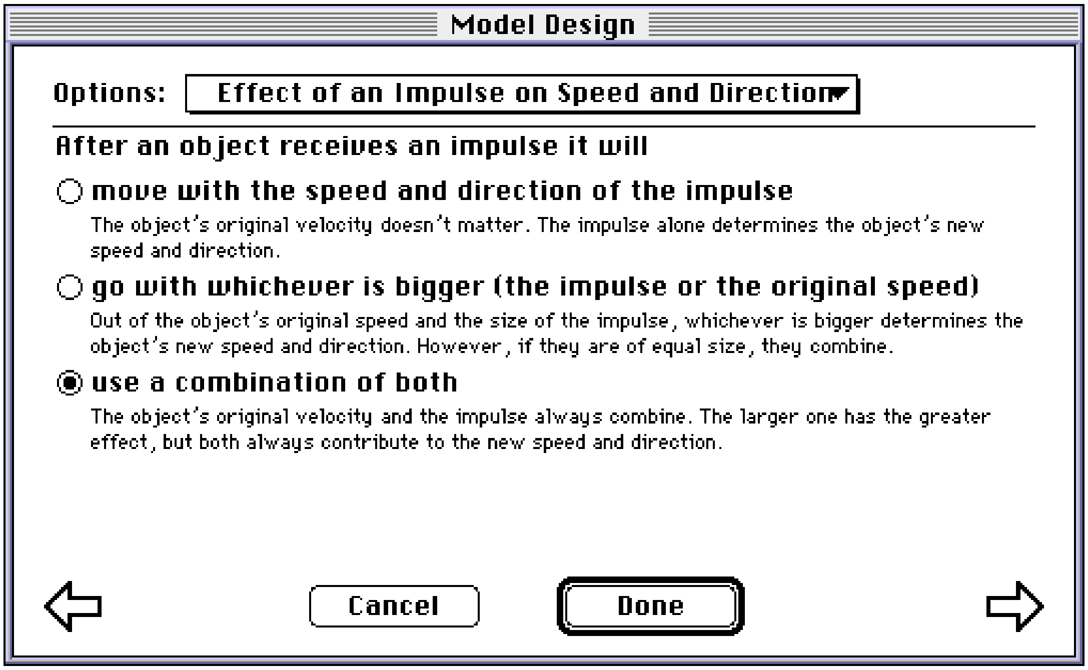
During each timestep an object's speed will

● remain the same
Only forces can change an object's speed.

○ decrease
In addition to the effects of any forces acting on it, the object will lose a little speed during each timestep.

○ increase
In addition to the effects of any forces acting on it, the object will gain a little speed during each timestep.

Figure 16. Revised model design options for motion independent of forces.



Options: Effect of an Impulse on Speed and Direction

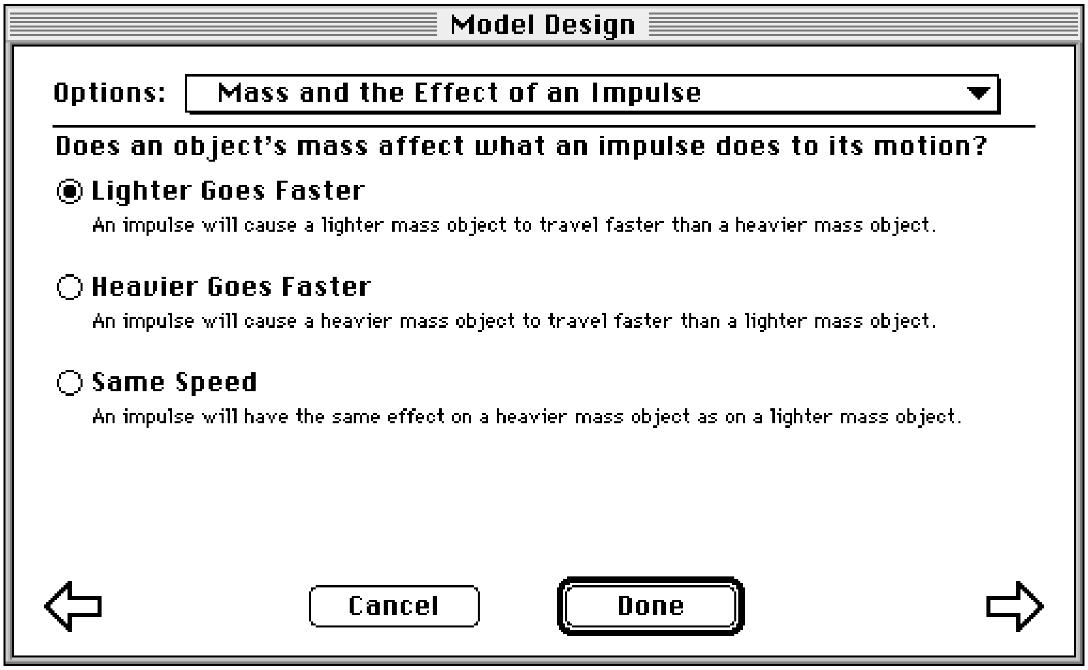
After an object receives an impulse it will

○ move with the speed and direction of the impulse
The object's original velocity doesn't matter. The impulse alone determines the object's new speed and direction.

○ go with whichever is bigger (the impulse or the original speed)
Out of the object's original speed and the size of the impulse, whichever is bigger determines the object's new speed and direction. However, if they are of equal size, they combine.

● use a combination of both
The object's original velocity and the impulse always combine. The larger one has the greater effect, but both always contribute to the new speed and direction.

Figure 17. Revised model design options for the effect of an impulse on speed and direction.



Options: Mass and the Effect of an Impulse

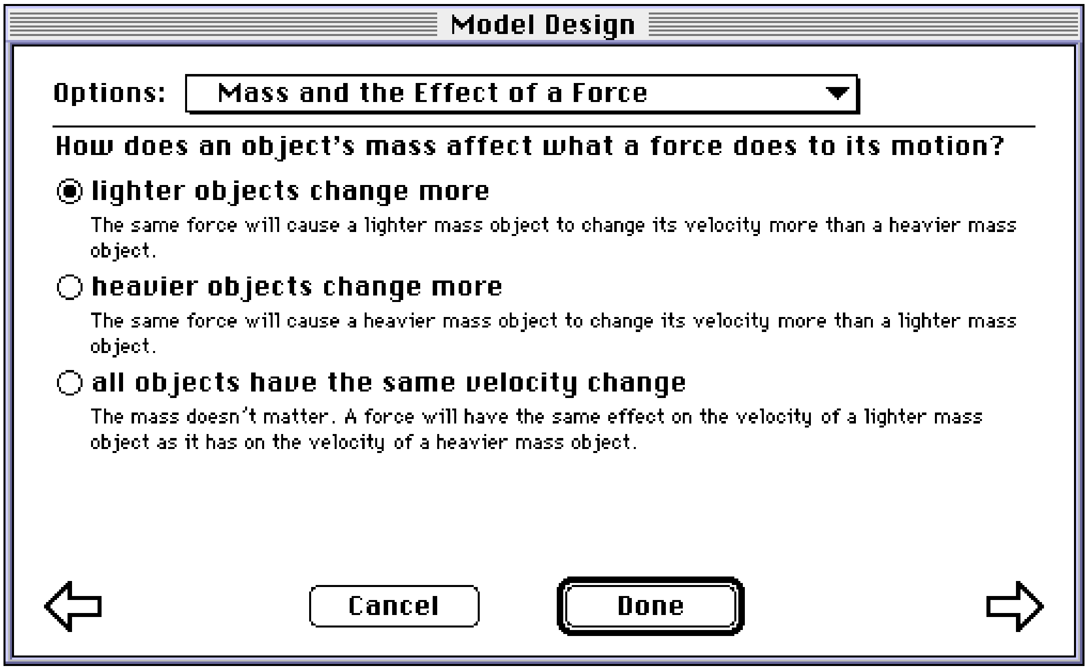
Does an object's mass affect what an impulse does to its motion?

● **Lighter Goes Faster**
An impulse will cause a lighter mass object to travel faster than a heavier mass object.

○ **Heavier Goes Faster**
An impulse will cause a heavier mass object to travel faster than a lighter mass object.

○ **Same Speed**
An impulse will have the same effect on a heavier mass object as on a lighter mass object.

Figure 18. Original model design options for mass and the effect of an impulse.



Options: Mass and the Effect of a Force

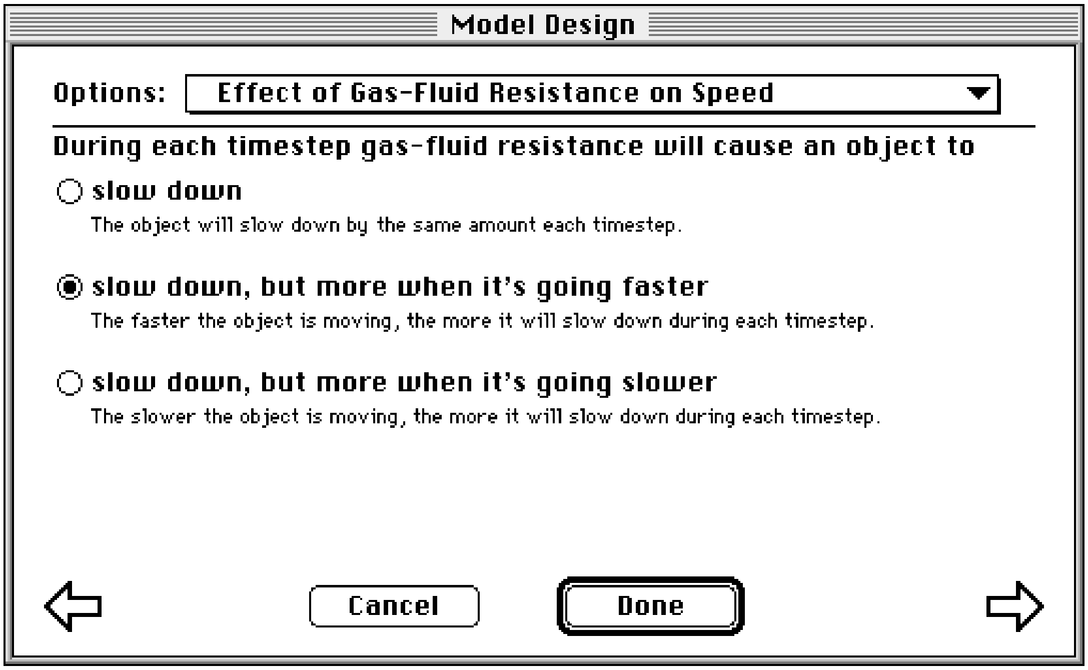
How does an object's mass affect what a force does to its motion?

● **lighter objects change more**
The same force will cause a lighter mass object to change its velocity more than a heavier mass object.

○ **heavier objects change more**
The same force will cause a heavier mass object to change its velocity more than a lighter mass object.

○ **all objects have the same velocity change**
The mass doesn't matter. A force will have the same effect on the velocity of a lighter mass object as it has on the velocity of a heavier mass object.

Figure 19. Revised model design options for mass and the effect of a force.



Options: Effect of Gas-Fluid Resistance on Speed

During each timestep gas-fluid resistance will cause an object to

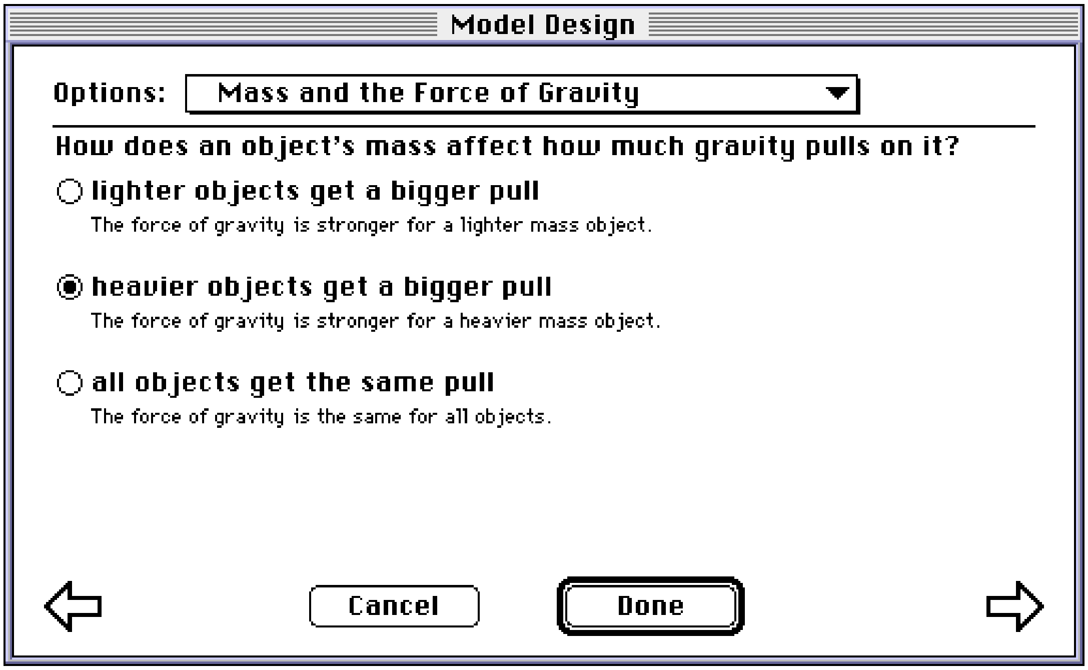
○ **slow down**
The object will slow down by the same amount each timestep.

● **slow down, but more when it's going faster**
The faster the object is moving, the more it will slow down during each timestep.

○ **slow down, but more when it's going slower**
The slower the object is moving, the more it will slow down during each timestep.

Figure 20. Revised model design options for the effect of fluid resistance on speed.

As we had generalized our inertia law to apply to the gravity context as well, we saw an opportunity to address a particularly difficult concept in a new way. By simply adding a new set of Model Design options to specify the relationship between an object's mass and the strength of the force of gravity acting on it (see Figure 21), we suddenly had a rich environment in which to explore the relationship between an object's mass and the rate at which it falls (neglecting air resistance). Schwarz's earlier research (1995) showed how difficult this concept is for students, most of whom think that heavier objects fall faster, and none of whom can give the Newtonian interpretation, even if they do believe that all objects fall at the same rate. We hoped that the Model Design feature might help students (assuming that they had selected the Newtonian options) to appreciate how during each timestep these two mass laws, each with an opposite effect on the object's velocity change, could effectively cancel one another out. If so, then this would be yet another advantage of the shift toward a mechanistic focus in our law descriptions.



Options: Mass and the Force of Gravity

How does an object's mass affect how much gravity pulls on it?

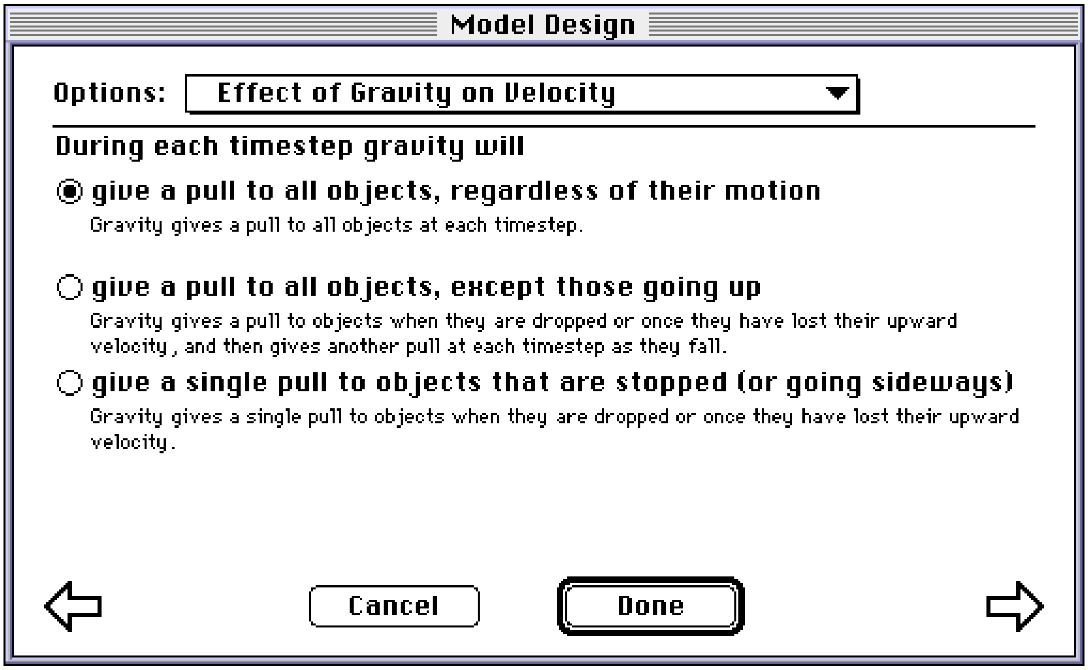
○ lighter objects get a bigger pull
The force of gravity is stronger for a lighter mass object.

● heavier objects get a bigger pull
The force of gravity is stronger for a heavier mass object.

○ all objects get the same pull
The force of gravity is the same for all objects.

Figure 21. New model design options for mass and the force of gravity.

Converting the effect of gravity on velocity options from descriptions of contextualized empirical results to general, causal mechanisms proved to be the most challenging redesign task. We needed to generalize the law options so that they applied to more than just falling objects, and we had to describe the effects on a timestep by timestep basis. As mentioned previously, all students know that "what goes up must come down," but few are able to describe the underlying mechanism in detail. In fact, even students who've completed the standard ThinkerTools curriculum often have trouble identifying gravity as the cause of objects slowing down immediately after they are thrown upward. Many students think that gravity can affect an object thrown upward only after it reaches the top of its trajectory (Clement, 1982). It seemed appropriate, therefore, to make the underlying causality explicit in our law options so that students could analyze and resolve these issues (see Figure 22). Note that while our new non-Newtonian gravity options specify a context for their application, the Newtonian option does not. We hoped that if students could see the difference in character between these options, they could come to appreciate the simplicity of a gravity law that acted at all times on all objects. The truly difficult part was drawing a distinction between the option that would result in a constant falling speed (i.e., “give a single pull to objects that are stopped (or going sideways)”) and the other two options, while still making the description general enough to cover two-dimensional ballistic motion as well. Our group was concerned that the awkward wording of our new gravity law options would make it difficult for students to predict and/or evaluate the behavior of objects obeying those laws, but decided to go ahead with a small trial before attempting further revision.



Options: Effect of Gravity on Velocity

During each timestep gravity will

● give a pull to all objects, regardless of their motion
Gravity gives a pull to all objects at each timestep.

○ give a pull to all objects, except those going up
Gravity gives a pull to objects when they are dropped or once they have lost their upward velocity, and then gives another pull at each timestep as they fall.

○ give a single pull to objects that are stopped (or going sideways)
Gravity gives a single pull to objects when they are dropped or once they have lost their upward velocity.

Figure 22. Revised model design options for the effect of gravity on velocity.

To summarize the revisions to the Model Design feature, we shifted our focus away from the descriptions of overall behavior that characterized the models our ThinkerTools students had developed in the past, toward the causal, mechanistic descriptions that exemplify the scientific models we wanted them to develop. Each of our new law options now specified how it would affect the behavior of an object during a simulation timestep, and it was clearer how these effects would combine. We had also de-contextualized our laws into more general principles with the widest possible scope, resulting in a dramatic simplification of the impulse options. The differential contextualization of the (non-Newtonian vs. Newtonian) gravity options highlighted the attractiveness of this property in a physical law. Appendix A compares the original and revised versions of the Model Design options for each subdomain. Given the extent of these changes, our group was interested in whether students could still locate their own preconceptions within the Model Design options now available to them, or whether we might have thrown the constructivist baby out with the bath water.

Methods

To shed some light on this question, I conducted individual, videotaped interviews with eight students from a sixth grade class who had seen neither the ThinkerTools curriculum nor the simulation software. During these one hour interviews, each student was asked to answer multiple choice questions from a written Contextual Concept Test, with two questions for each Model Design subdomain (see Table 3). The multiple choice answer options for these questions were based on the behavior predicted by the analogous Model Design options. Once the student had answered both CCT questions for a given subdomain, they were shown the ThinkerTools simulation software and asked to choose a law from that page of Model Design options. This process was then repeated for each Model Design subdomain (the entire CCT appears as Appendix D.) After all subdomains had been covered, their complete Model Design was then used to simulate the behavior of the objects in the more familiar ($\mathrm{CCT}_{\mathrm{familiar}}$) of the two questions from each subdomain (notes were added in both Table 3 and Appendix D to indicate which of the CCT questions was simulated.) The students were asked whether the simulation looked correct. If not, they reviewed both their CCT predictions and their Model Design laws to resolve the conflict.

Question 4.1 [$\text{CCT}_{\text{familiar}}$]
Imagine two balls resting on a smooth floor. The balls are exactly the same except that one is four times as heavy as the other one. Now suppose that you give the same sized kick to both balls at the same time. After you kick the balls, what can be said about their speeds?

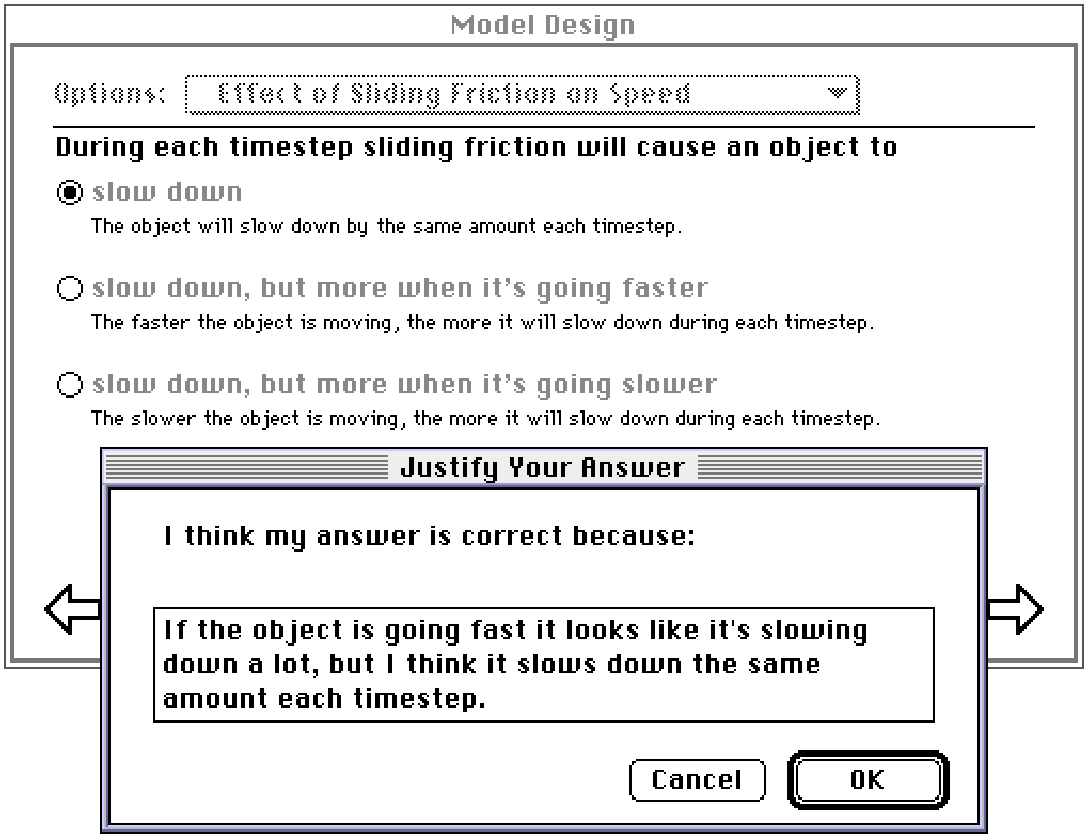
a) The lighter one will be going faster.
b) The heavier one will be going faster.
c) Both balls will have the same speed.

Question 4.2 [$\text{CCT}_{\text{less familiar}}$]
Suppose you have two shopping carts, one full of light stuff (like bread and cereal) and the other full of heavy stuff (like juice and canned foods). If the two carts are stopped and then you give the same sized push to both, what can be said about their speeds?

a) The lighter one will be going faster.
b) The heavier one will be going faster.
c) Both carts will have the same speed.

Table 3. Contextual Concept Test questions.

The two questions ($\text{CCT}_{\text{familiar}}$ and $\text{CCT}_{\text{less familiar}}$) in each subdomain were designed to stretch the students' preconceptions across as broad a set of contexts as possible before asking them to evaluate law options. After answering each question, the students were encouraged to explain the reasoning underlying their answers. Similarly, after making each Model Design option choice, the software requested a written justification for their selection (see Figure 23). It was hoped that (in addition to illuminating the students' reasoning processes) these approaches might mitigate somewhat the challenge of extending their contextualized preconceptions so that they could be compared with and thus aid in the selection of general physical laws. As students describe and justify their models, they are forced to come up with metaphors for explaining them, hopefully making their knowledge more general, and thereby facilitating transfer.



Options: Effect of Sliding Friction on Speed

During each timestep sliding friction will cause an object to

● slow down
The object will slow down by the same amount each timestep.

○ slow down, but more when it's going faster
The faster the object is moving, the more it will slow down during each timestep.

○ slow down, but more when it's going slower
The slower the object is moving, the more it will slow down during each timestep.

I think my answer is correct because:

If the object is going fast it looks like it's slowing down a lot, but I think it slows down the same amount each timestep.

Figure 23. Justifying a Model Design selection.

Constructing CCT questions with answers analogous to the gravity and velocity Model Design options (see Figure 22) was extremely difficult, as we were attempting to cover two very different misconceptions within the same subdomain: 1) objects fall at a constant rate, and 2) gravity acts only on falling objects. My approach was to assess this subdomain using two different CCT question types, one for each misconception (see Table 4). Instead of a direct one-to-one correspondence between the CCT answers and the Model Design options, a method was employed to predict the Model Design choice from the combination of answers to two CCT questions (see Table 5). Note as well the mechanistic (rather than behavioristic) nature of the “gravity acts only on falling objects” misconception, which made its CCT questions difficult to answer empirically.

Question 6.1
Tom drops a ball and carefully measures its speed as it falls. Just before the ball hits the ground its speed is 20 feet per second. Suppose that he drops the same ball again, but this time from twice as high. How fast will the ball be moving just before it hits the ground?

a) 20 feet per second
b) faster than 20 feet per second

Question 7.1
Suppose you throw a ball straight upward. When does gravity begin to affect its motion?

a) as soon as it leaves your hand
b) as soon as it stops going upward

Table 4. CCT questions for the effect of gravity on velocity.

		When does gravity begin acting?	
		right away	when objects stop
Objects fall at a constant speed?	yes	(unlikely)	Model 3
	no	Model 1	Model 2

Model 1: Gravity will give a pull to all objects, regardless of their motion.
Model 2: Gravity will give a pull to all objects, except those going up.
Model 3: Gravity will give a single pull to objects that are stopped (or going sideways).

Table 5. Method employed for predicting gravity rule selection from CCT answers.

Since none of the subjects had any experience with either scientific modeling or simulation software, let alone the specifics of the ThinkerTools program or its Model Design feature, a significant portion of the one hour interview was devoted to explaining how ThinkerTools simulates real world objects and how the Model Design options selected would control this behavior. This discussion followed the first two CCT questions, and began with a demonstration of how ThinkerTools could simulate two familiar scenarios: a ball bouncing down a ramp and a car accelerating. The latter was backed up with a flip book animation of the same scenario. The flip book animation provided a context for introducing the idea of a simulation timestep, now critical for evaluating Model Design options. The terms “impulse,” “velocity,” and “mass” which also appear in the text of the Model Design options were defined as well. Finally, the relationship between an object’s speed and the distance it travels during a timestep was demonstrated. The entire interview protocol is included as Appendix E.

Results

Contextualization of student preconceptions. We hypothesized that student preconceptions would be context-bound, so the CCT questions were chosen so that the students had the opportunity to apply what we considered a single general principle to two very different contexts ($\mathrm{CCT}_{\mathrm{familiar}}$ and $\mathrm{CCT}_{\mathrm{less\ familiar}}$). I tested this hypothesis by checking the consistency of their answers between the two contexts[4] , and found that the mean number of agreements out of 6 possible was $M = 2.86$, $SD = 0.69$, which corresponds to 48%. This differs significantly from the level expected by chance alone (2 or 33%) with $t_6 = 3.28$, $p = .008$, but not by a great deal. This indicates that although the students’ answers to the two contexts were indeed related, the relationship was not very strong.

Match between familiar context and model design selection. The question we were most interested in was whether there would be agreement between student preconceptions and their initial Model Design law choices. To test this, we compared the student answers to the $\mathrm{CCT}_{\mathrm{familiar}}$ questions with their initial Model Design selections. We found that the mean number of agreements (again, out of six possible) was $M = 3.71$, $SD = 2.06$, which corresponds to 62%. This differs

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[4] As noted before, the method described in Table 5 was employed to combine the answers to two CCT questions in order to generate the last of the six Model Design sub-domains (effect of gravity on velocity). For this and the analyses that follow, we treated the combination as a single question with three possible choices.

significantly from the chance level with $t_6 = 2.20$, $p = .03$, suggesting that most students were able to make use of their preconceptions in evaluating and selecting physical laws, and perhaps these preconceptions were more useful for this than they were for answering questions in a less familiar context. Note that there was no significant agreement between the $\text{CCT}_{\text{less familiar}}$ answers and the Model Design selections ($M = 2.29$, $SD = 1.11$, $t_6 = .679$, $p = .26$).

The students' written justifications for their Model Design selections also showed that they were making use of their preconceptions. For example, one student justified her selection of the law "heavier objects get a bigger pull" by writing, "since heavier objects are harder to lift I think gravity also has a harder time pulling it." Another student justified her selection of the law "after an object receives an impulse it will go with whichever is bigger (the impulse or the original speed)" by writing, "It depends on how big the object is and how big the person or whoevers hitting it." Still another student justified her selection of the law "In addition to the effects of any forces acting on it, the object will lose a little speed during each timestep" by writing, "if the object's moving along like for a while it will slow down because I saw this show on rollercoasters and it slows down after a while because the force is not as strong anymore." The complete set of the students' initial Model Design selections and the justifications for each are included as Appendix B.

Reasoning from simulation results. After viewing the simulation results, the students were given the task of resolving conflicts between their initial $\text{CCT}_{\text{familiar}}$ predictions and the simulation results. Here, the relationship between the two was tested in the opposite direction, that is, the students had to consider how their Model Design options explained the simulation results. The students had the opportunity to revise either their answer to the $\text{CCT}_{\text{familiar}}$ question or their Model Design selection, in order to resolve the conflict. After completing this task, we found that their (revised) $\text{CCT}_{\text{familiar}}$ answers matched their (revised) Model Design option choices even more often than their initial CCT$_{\text{familiar}}$ answers matched their initial Model Design option choices. The mean number of agreements (again, out of six possible) was *M* = 5.00, *SD* = 0.82, which corresponds to 83%. This differs significantly from the chance level with $t_6 = 9.71$, $p < .001$, suggesting that the students usually understood why their initial Model Design options did not agree with their initial CCT$_{\text{familiar}}$ answers. Note also that they were able to resolve these conflicts without resorting to trial and error; no student made more than a single revision within a subdomain. The complete set of the students' revised Model Design selections and the justifications for each are included as Appendix C.

Some of these conflicts, however, proved more difficult to resolve than others. One student clung to his preconception about the effect of mass on the force of gravity, even though he understood how it resulted in a ThinkerTools simulation that contradicted his real world experience. Note that in the following transcript and those that follow, "I" stands for the interviewer (myself), and "S" stands for student:

I: Which do you think gravity pulls harder on, a soccer ball, a bowling ball, or gravity pulls the same amount on both?

S: I think it pulls the same amount on both, because the soccer ball's lighter, but like when Galileo took the two different sized balls and dropped them from the tower, they both fell at the same time. I think it pulls the same on both, except the soccer ball feels lighter because the bowling ball is solid and the soccer ball is hollow. But since there's the same force of gravity pulling on both of them, I mean, gravity pulls the same on both of them.

[The student chooses the analogous MD option. Later in the interview, we run the simulation:]

I: Here's a light ball and a heavy ball, and we're dropping them. So just hit the spacebar to drop them, and then tell me whether it's correct.

S: What I said, or what the thing is doing.

I: What it’s doing.

S: [Student runs the simulation, and the lighter ball clearly falls faster than the heavier ball.] Oh. No, because I mean... I don’t think, because if the light ball and the heavy ball, unless [pause] Are they both the same size?

I: They’re the same size. They’re exactly the same, except one is heavier.

S: Yeah, well then they would fall the same. I don’t think the heavy ball would fall slower. If anything, the heavy ball would fall faster, because it’s heavier, but it wouldn’t fall slower than the light ball.

I: Let’s try and figure out maybe what went wrong. So let’s look at what you told it about the effect of gravity on velocity. You said it gives a pull to all objects regardless of their motion. Do you think that’s the right answer?

S: Let’s see. It gives a pull on all objects, so yeah. I mean, it’s falling down, so it gives a pull to all objects, even if they’re going across or down, because its always pulling on them. Yeah.

I: How about mass and the force of gravity? How does an object’s mass affect how much gravity pulls on it? Lighter objects get a bigger pull, heavier objects get a bigger pull, or all objects get the same pull?

S: Well, I don’t know. To fix it so that it goes the way I think, you would have to do heavier objects get a bigger pull, so that it goes the way I think it should. But I think that all objects get the same pull, because gravity pulls the same on all things.

I: Are you interested in giving it a try and seeing if that fixes it?

S: Sure. [Student selects the “heavier objects get a bigger pull” option, and then the justification dialog appears.]

I: OK, so type in why you think this might be true, or you just don’t think this is true.

S: I don’t think it’s true, but I think it’ll fix the problem.

I: Put that down.

S: [Student types, “I don't think this is true, but it will make the program behave the way I want it to.”]

I: So let’s try. [Student runs simulation, and the balls fall at the same rate.]

S: Yeah, that’s how I think it goes.

I: So this is how you think it goes, but the rules you don’t agree with.

S: Right.

This student appears to understand how his mass and the force of gravity rule affects the simulation, and he was able to select the option to give the overall behavior he desired. It appears that he had previously reasoned from an empirical result (i.e., Galileo’s purported experiment) back to a conclusion about the force of gravity, and was holding strongly to this preconception. Perhaps with more time he could have come to understand the difference between the empirical result on which his preconception was based and the mechanisms underlying it.

The student in the following transcript had chosen the Newtonian options for both the law for mass and the effect of a force, and the law for mass and the force of gravity. The first time he simulated dropping objects of different masses, however, he was confused because the two balls fell at the same rate.

I: So, what are they doing?

S: They’re both keeping at an equal speed when one’s lighter and one’s heavier.

I: And why do you think that’s wrong?

S: I think it’s wrong because gravity would kind of be working with the larger weight of this ball to pull it down a little faster than the lighter ball, and the lighter ball would like have like less coming into it. Well, it would get less of a pull, because it really doesn’t need that much of a pull on it. The lighter ball doesn’t need a big pull, because it’s a lighter object, and the heavier object needs a bigger pull to get down to the ground.

I: OK, so you said that...

S: Hang on a second.

I: I'm hanging.

S: It gets the lighter pull, and gravity [points at heavier ball] gets the heavier pull, but they're both going at the... One got a lighter pull and one got a heavier pull, so they probably would be going the same speed.

This transcript shows quite dramatically the potential of the Model Design feature for facilitating conceptual change. The student not only understood that the simulation was obeying the laws he had chosen; he was also able to reason effectively about how combinations of these laws explained the overall simulation results. His conclusion also appeared to extend beyond the context of the simulation into the real world.

Given the difficulty of this particular concept, it's surprising that a sixth grade student could make this much progress in such a short amount of time. During the Spring of 1994, Schwarz (1995) studied the work of seventh and eighth grade students in the standard ThinkerTools curriculum who had spent several weeks developing laws to explain both the effect of inertia and the force of gravity. Although more than half of the students correctly stated on a posttest that objects of different masses would fall at the same rate (neglecting air resistance), none of their explanations were consistent with the laws they had developed. Not a single student gave the Newtonian interpretation, even among the 22 who had designed and conducted independent projects to determine the relationship between mass and the effect of gravity. During her follow-up interviews, she found that students had apparently compartmentalized their knowledge about the effect of inertia, often linking it inappropriately to static friction. None of these students could see that the inertia law extended beyond the context in which it was originally studied, and they systematically rejected her repeated suggestions that this law might be useful for explaining the behavior of a falling object.

In contrast, we believe that the Model Design feature helped the student in the above transcript understand the mechanism and broad scope of the inertia law, resulting in better knowledge integration and thus a greater capacity for explaining the behavior of objects under the influence of gravity. Perhaps given more time to experiment with the activity in single-step mode, where the simulation engine articulates its application of the laws during each timestep, more students could have reached the same interpretation.

Conclusions

As mentioned before, the abstract nature of the scientific modeling process has made it particularly difficult for students in the standard ThinkerTools curriculum. The ThinkerTools Model Design feature effectively bridges the gap between the abstract and the concrete by providing an environment for students to explore their preconceptions, extend them into more general laws, and then evaluate the implications of these and other physical models. Students in a Model Design curriculum such as the one Schwarz created can come to appreciate how just a few basic principles can govern the behavior of an infinite set of dissimilar experiments. Whereas the standard ThinkerTools curriculum allowed students to build and run computer microworlds, our model designers now have the additional opportunity to learn how a computer simulation engine uses scientific models to bring these microworlds to life.

It would appear that de-contextualizing the Model Design options and recharacterizing them in mechanistic terms resulted in a more appropriate method of representing alternate physical laws. These new options have more of the attributes we would like our students to appreciate in scientific models: generality, independence, and clear mechanism. Although their preconceptions are contextualized and lack consistency, our students are apparently still able to see the relationship between these preconceptions and the de-contextualized physical law options now available to them. The new focus on mechanism has not only made the inner workings of the simulation engine more visible, it has also provided an opportunity for students to explore law interactions, such as the interplay between inertia and the force of gravity.

Future Research

The small amount of time spent with each student during the interviews described above placed serious limitations on the amount of instruction, exploration, and analysis that could be conducted. Although the results were promising, they raised more interesting questions than they answered. A follow-up study with a larger group of students, and at least three 1-hour sessions per student would be a first step toward answering some of these.

If the Model Design feature does help students develop and appreciate more general physical models, we should find that they have a greater ability to transfer their models to novel contexts. It would be interesting to see whether after their brief opportunity to evaluate and experiment with alternate physical laws, the students are more likely to apply their revised Model Design choice to the other context on the CCT, resulting in greater agreement between the two CCT contexts.

As mentioned above, the “Talking Model” feature narrates the application of the physical laws chosen during single-step mode. For example, if the Newtonian setting for motion independent of forces is chosen the simulation will say, “Without a force like friction acting on me, I will stay the same speed” during each timestep. By running simulations in single-step mode, the students would hopefully do an even better job of finding models that match their preconceptions about force and motion. Their understanding of these models might also prove more robust, as reflected in their performance on subsequent transfer tests. More students might also arrive at the Newtonian Model Design options after they’ve had more time to examine the mechanisms in action on a timestep by timestep basis.

The textual form currently used to describe the Model Design options makes them immediately accessible to students, but lacks some formality. We have considered allowing students to toggle the Model Design interface between these textual descriptions and mathematical descriptions of the laws (e.g., $v_{new} = v_{old} - k \bullet v_{old}$). In addition to elaborating the mechanism underlying the simulation, we feel that this capability could help the students draw connections between the Model Design options and the formal physical laws that support quantitative analysis.

Finally, it might do well to reexamine the multiple-choice paradigm. I had planned to ask students whether they thought that the correct answer might be missing, or how they might modify either a CCT answer or a Model Design option to bring it in greater agreement with their own preconceptions. An entire one hour session might have been devoted to exploring the kind of models students could construct simply from their own preconceptions, given the opportunity to evaluate a few provided to them. Even if we decide to keep our multiple-choice paradigm, the student responses would help us further refine the options we make available.

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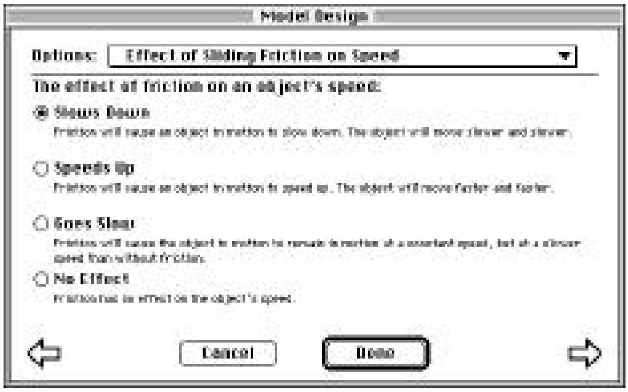
Appendix A

ThinkerTools Model Design Feature

Original (Version 4.1)



Options: Effect of Sliding Friction on Speed

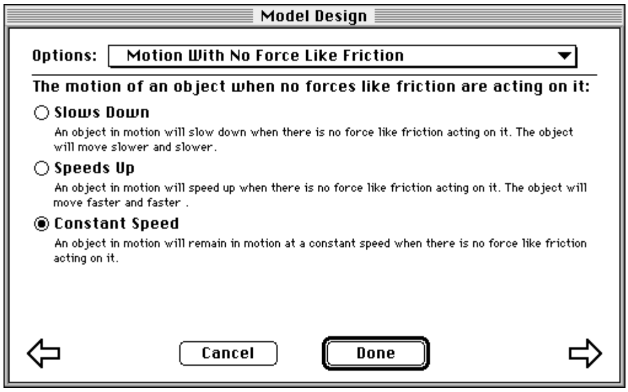
The effect of friction on an object's speed:

● Slows Down
Friction will cause an object in motion to slow down. The object will move slower and slower.

○ Speeds Up
Friction will cause an object in motion to speed up. The object will move faster and faster.

○ Goes Slow
Friction will cause the object in motion to remain in motion at a constant speed, but at a slower speed than without friction.

○ No Effect
Friction has no effect on the object's speed.



Options: Motion With No Force Like Friction

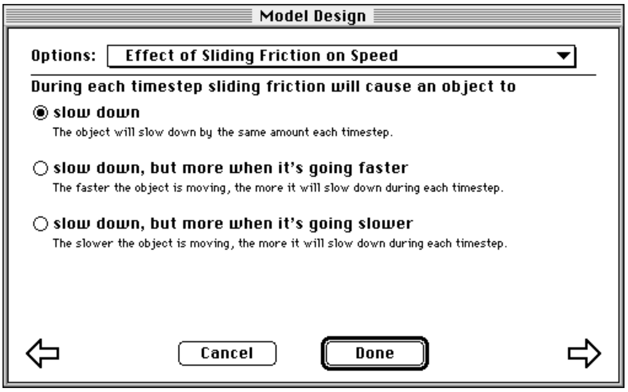
The motion of an object when no forces like friction are acting on it:

○ Slows Down
An object in motion will slow down when there is no force like friction acting on it. The object will move slower and slower.

○ Speeds Up
An object in motion will speed up when there is no force like friction acting on it. The object will move faster and faster .

● Constant Speed
An object in motion will remain in motion at a constant speed when there is no force like friction acting on it.

Revised (Version 4.2)



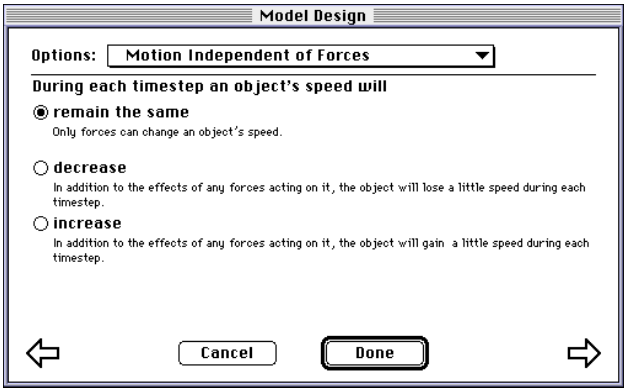
Options: Effect of Sliding Friction on Speed

During each timestep sliding friction will cause an object to

● slow down
The object will slow down by the same amount each timestep.

○ slow down, but more when it's going faster
The faster the object is moving, the more it will slow down during each timestep.

○ slow down, but more when it's going slower
The slower the object is moving, the more it will slow down during each timestep.



Options: Motion Independent of Forces

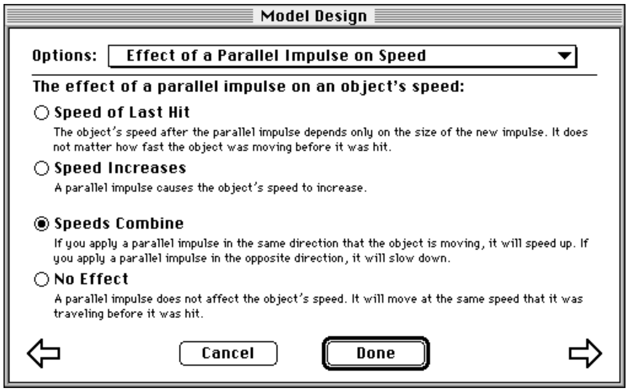
During each timestep an object's speed will

● remain the same
Only forces can change an object's speed.

○ decrease
In addition to the effects of any forces acting on it, the object will lose a little speed during each timestep.

○ increase
In addition to the effects of any forces acting on it, the object will gain a little speed during each timestep.

Original (Version 4.1)



Options: Effect of a Parallel Impulse on Speed

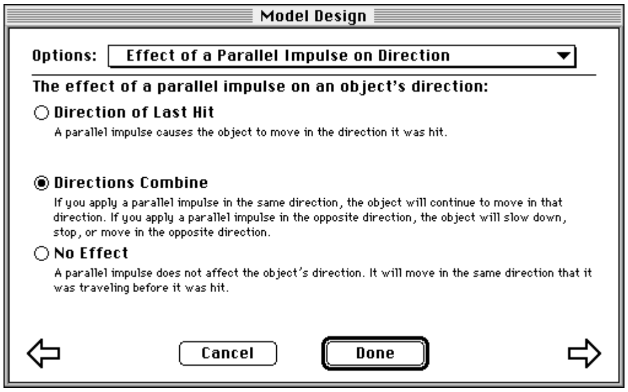
The effect of a parallel impulse on an object's speed:

○ **Speed of Last Hit**
The object's speed after the parallel impulse depends only on the size of the new impulse. It does not matter how fast the object was moving before it was hit.

○ **Speed Increases**
A parallel impulse causes the object's speed to increase.

● **Speeds Combine**
If you apply a parallel impulse in the same direction that the object is moving, it will speed up. If you apply a parallel impulse in the opposite direction, it will slow down.

○ **No Effect**
A parallel impulse does not affect the object's speed. It will move at the same speed that it was traveling before it was hit.



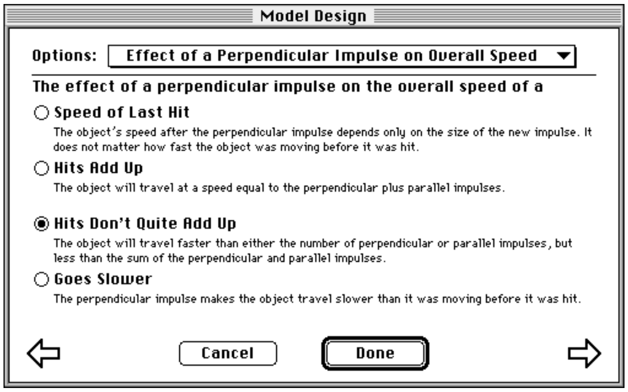
Options: Effect of a Parallel Impulse on Direction

The effect of a parallel impulse on an object's direction:

○ **Direction of Last Hit**
A parallel impulse causes the object to move in the direction it was hit.

● **Directions Combine**
If you apply a parallel impulse in the same direction, the object will continue to move in that direction. If you apply a parallel impulse in the opposite direction, the object will slow down, stop, or move in the opposite direction.

○ **No Effect**
A parallel impulse does not affect the object's direction. It will move in the same direction that it was traveling before it was hit.



Options: Effect of a Perpendicular Impulse on Overall Speed

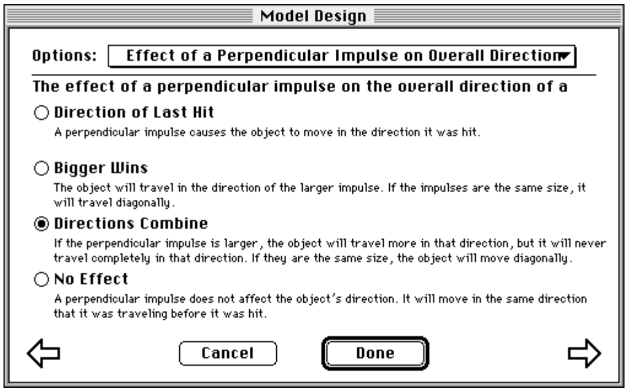
The effect of a perpendicular impulse on the overall speed of a

○ **Speed of Last Hit**
The object's speed after the perpendicular impulse depends only on the size of the new impulse. It does not matter how fast the object was moving before it was hit.

○ **Hits Add Up**
The object will travel at a speed equal to the perpendicular plus parallel impulses.

● **Hits Don't Quite Add Up**
The object will travel faster than either the number of perpendicular or parallel impulses, but less than the sum of the perpendicular and parallel impulses.

○ **Goes Slower**
The perpendicular impulse makes the object travel slower than it was moving before it was hit.



Options: Effect of a Perpendicular Impulse on Overall Direction

The effect of a perpendicular impulse on the overall direction of a

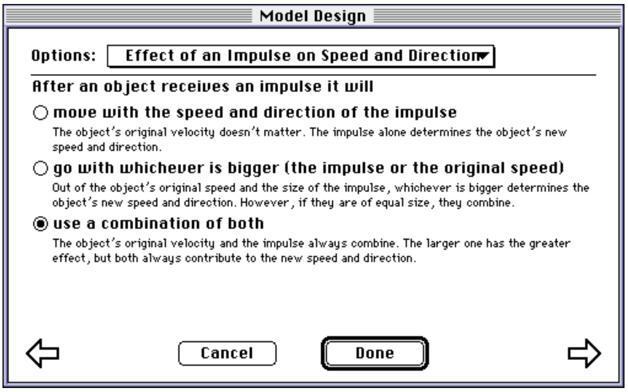
○ **Direction of Last Hit**
A perpendicular impulse causes the object to move in the direction it was hit.

○ **Bigger Wins**
The object will travel in the direction of the larger impulse. If the impulses are the same size, it will travel diagonally.

● **Directions Combine**
If the perpendicular impulse is larger, the object will travel more in that direction, but it will never travel completely in that direction. If they are the same size, the object will move diagonally.

○ **No Effect**
A perpendicular impulse does not affect the object's direction. It will move in the same direction that it was traveling before it was hit.

Revised (Version 4.2)



Options: Effect of an Impulse on Speed and Direction

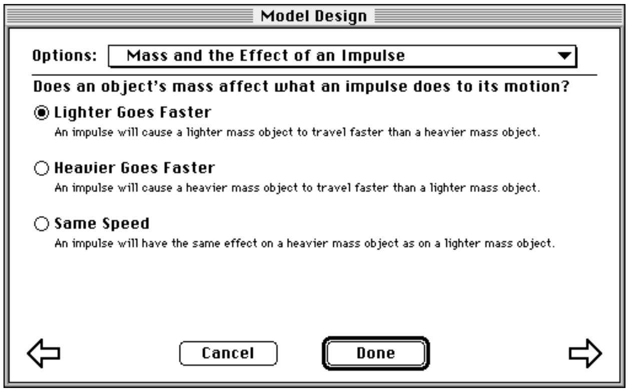
After an object receives an impulse it will

○ **move with the speed and direction of the impulse**
The object's original velocity doesn't matter. The impulse alone determines the object's new speed and direction.

○ **go with whichever is bigger (the impulse or the original speed)**
Out of the object's original speed and the size of the impulse, whichever is bigger determines the object's new speed and direction. However, if they are of equal size, they combine.

● **use a combination of both**
The object's original velocity and the impulse always combine. The larger one has the greater effect, but both always contribute to the new speed and direction.

Original (Version 4.1)



Options: Mass and the Effect of an Impulse

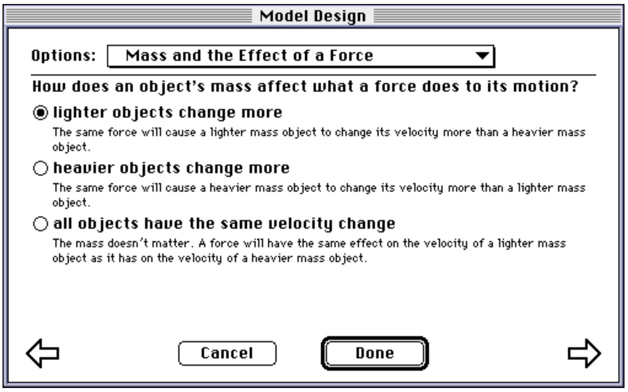
Does an object's mass affect what an impulse does to its motion?

● Lighter Goes Faster
An impulse will cause a lighter mass object to travel faster than a heavier mass object.

○ Heavier Goes Faster
An impulse will cause a heavier mass object to travel faster than a lighter mass object.

○ Same Speed
An impulse will have the same effect on a heavier mass object as on a lighter mass object.

Revised (Version 4.2)



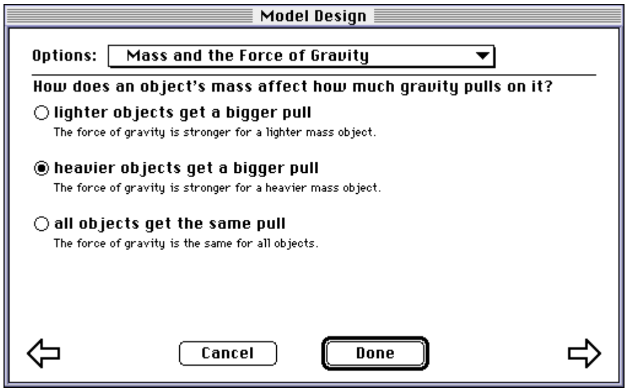
Options: Mass and the Effect of a Force

How does an object's mass affect what a force does to its motion?

● lighter objects change more
The same force will cause a lighter mass object to change its velocity more than a heavier mass object.

○ heavier objects change more
The same force will cause a heavier mass object to change its velocity more than a lighter mass object.

○ all objects have the same velocity change
The mass doesn't matter. A force will have the same effect on the velocity of a lighter mass object as it has on the velocity of a heavier mass object.



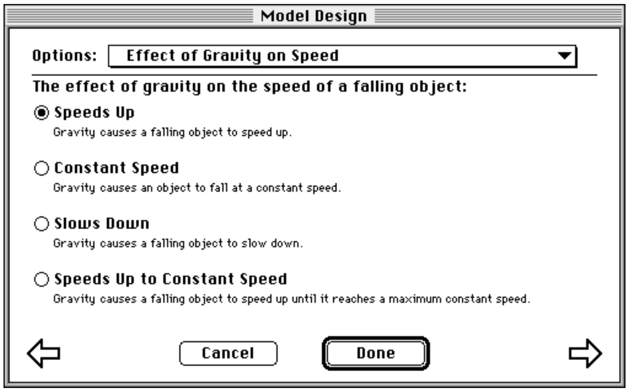
Options: Mass and the Force of Gravity

How does an object's mass affect how much gravity pulls on it?

○ lighter objects get a bigger pull
The force of gravity is stronger for a lighter mass object.

● heavier objects get a bigger pull
The force of gravity is stronger for a heavier mass object.

○ all objects get the same pull
The force of gravity is the same for all objects.



Options: Effect of Gravity on Speed

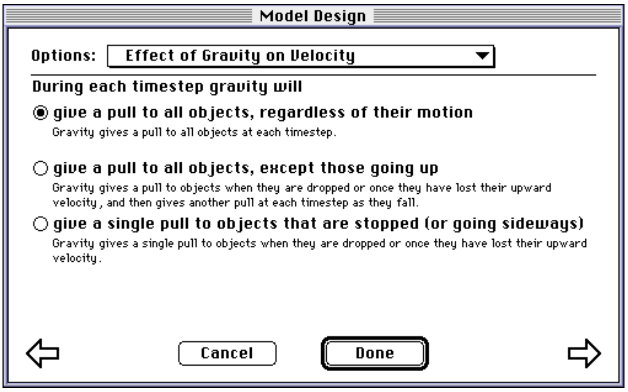
The effect of gravity on the speed of a falling object:

● Speeds Up
Gravity causes a falling object to speed up.

○ Constant Speed
Gravity causes an object to fall at a constant speed.

○ Slows Down
Gravity causes a falling object to slow down.

○ Speeds Up to Constant Speed
Gravity causes a falling object to speed up until it reaches a maximum constant speed.



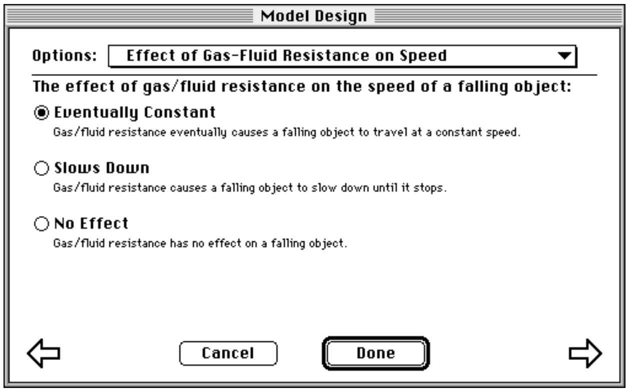
Options: Effect of Gravity on Velocity

During each timestep gravity will

● give a pull to all objects, regardless of their motion
Gravity gives a pull to all objects at each timestep.

○ give a pull to all objects, except those going up
Gravity gives a pull to objects when they are dropped or once they have lost their upward velocity, and then gives another pull at each timestep as they fall.

○ give a single pull to objects that are stopped (or going sideways)
Gravity gives a single pull to objects when they are dropped or once they have lost their upward velocity.



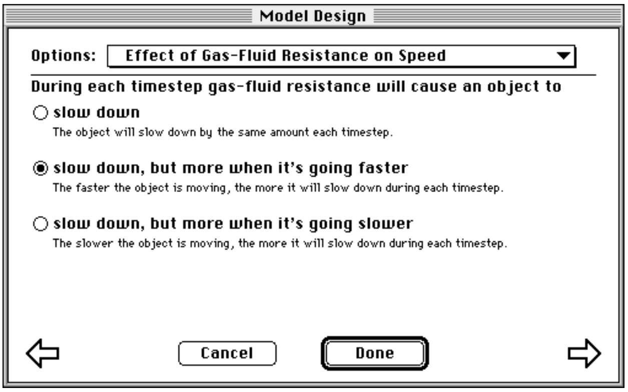
Options: Effect of Gas-Fluid Resistance on Speed

The effect of gas/fluid resistance on the speed of a falling object:

● Eventually Constant
Gas/fluid resistance eventually causes a falling object to travel at a constant speed.

○ Slows Down
Gas/fluid resistance causes a falling object to slow down until it stops.

○ No Effect
Gas/fluid resistance has no effect on a falling object.



Options: Effect of Gas-Fluid Resistance on Speed

During each timestep gas-fluid resistance will cause an object to

○ slow down
The object will slow down by the same amount each timestep.

● slow down, but more when it's going faster
The faster the object is moving, the more it will slow down during each timestep.

○ slow down, but more when it's going slower
The slower the object is moving, the more it will slow down during each timestep.

Appendix B

Initial Student Model Design Choices and Justifications

Effect of Sliding Friction on Speed

slow down (2 students):

1. each timestep it will slow down a little bit more untill it gradually stops
2. If the object is going fast it looks like it's slowing down a lot, but I think it slows down the same amount each timestep.

slow down, but more when it's going faster (3 students):

1. i think this is right because the faster the object is moving the more it will slow down.
2. it slows down faster than it stops is when it stpos it moves faster all the time.
3. as it goes fast it has to drop down a lot more, like skid.

slow down, but more when it's going slower (2 students):

1. just because
2. when I ride a bike and put on the brake, it slows down a little and then comes to a stop all of a sudden.

Motion Independent of Forces

remain the same (3 students):

1. just because
2. Only something from outside of an object can move it. It won't move by itself.
3. only when forces force does the object move, but if there was nothing pulling it, then why should it slow down?

decrease (3 students):

1. just because
2. the object has nothing pusing it along so it will avenchually slow down unless it is on a hill
3. if there are no forces on the object, the object will just decreaese the speed it was going.

increase (1 student):

1. it would have more speed than it had before.

Effect of an Impulse on Speed and Direction

move with the speed and direction of the impulse (0 students):

go with whichever is bigger (the impulse or the original speed) (2 students):

1. It depends on how big the object is and how big the person or whoevers hitting it.
2. if something is goeing at a slow speed and I hit it it wil go with the larger impuse because it wont go with a combination of slow and fast it will go fast

use a combination of both (5 students):

1. i think if the first person hits it really hard and then a second person hits it harder it will probably spin out of control in aknew direction
2. I think if an object is already moving the impulse will add to it even if the impulse is bigger because the object already had some velocity.
3. it gets more speed when they combine, if they don't it will go slower.
4. it would combine by going together like another way.
5. it's true that the larger one has more control over the direction, however there's still another amount of impulse/velocity from the other one.

Mass and the Effect of a Force

lighter objects change more (4 students):

1. a lighter object changes because if something hits it will go faster
2. the lighter objects are easier to kick and so they move faster.
3. a heavier object needs a bigger push to change its velocity.
4. if a bully pushes someone without much mass, they would go farther than someone with more mass because the the person with the most mass could overpower the force of the push.

heavier objects change more (1 student):

1. the heavier object will have a drastic chainge at the start with the speeds of the impulse

all objects have the same velocity change (2 students):

1. the lighter one will catch up to the heavier one eventually
2. if noe is heavier than one of the other sometimes they would go the same speed.

Mass and the Force of Gravity

lighter objects get a bigger pull (1 student):

1. just because

heavier objects get a bigger pull (5 students):

1. since heavier objects are harder to lift I think gravity also has a harder time pulling it
2. gravitie tends to pull harder on something that is heavier because its weight is puled along with the force of gravetie
3. on a heavier object gravity will pull harder so that it wont go that fast.
4. it would get a bigger pull than the ligher one.
5. the earth has a gravitational pull (unlike space), and it just pulls the heavier things down more.

all objects get the same pull (1 student):

1. there is the same amount of gravity pulling on both objects, gravity doesn't change for one object.

Effect of Gravity on Velocity

give a pull to all objects, regardless of their motion (5 students):

1. Gravity is always pulling regardless of the objects speed or direction
2. It depends on how hard you are throwing it, if you are throwing it really hard then the gravity gives it a smaller pull, if you are throwing it really light then the gravity gives it a bigger pull.
3. gravitie always gives pulls on an object regardless of upward or down word motion
4. gravity is always pulling the same on all objects, but the force that threw them determines when you see gravity affect them.
5. wherever you are on this earth, it will have a gravitational pull, even on a plane up in the air.

give a pull to all objects, except those going up (2 students):

1. once I threw a baseball in my back yard and it went up, but gravity didn't pull it until the ball went down, and so the ball won't go twice as far as you want it to.
2. when it gos up it pulls more why it is going up.

give a single pull to objects that are stopped (or going sideways) (0 students):

Appendix C

Revised Student Model Design Choices and Justifications

Effect of Sliding Friction on Speed

slow down (2 students):

1. each timestep it will slow down a little bit more untill it gradually stops
2. If the object is going fast it looks like it's slowing down a lot, but I think it slows down the same amount each timestep.

slow down, but more when it's going faster (3 students):

1. i think this is right because the faster the object is moving the more it will slow down.
2. it slows down faster than it stops is when it stpos it moves faster all the time.
3. as it goes fast it has to drop down a lot more, like skid.

slow down, but more when it's going slower (2 students):

1. just because
2. when I ride a bike and put on the brake, it slows down a little and then comes to a stop all of a sudden.

Motion Independent of Forces

remain the same (3 students):

1. gravity is always pulling something and the spaceship is being pulled around just like the planets
2. Only something from outside of an object can move it. It won't move by itself.
3. only when forces force does the object move, but if there was nothing pulling it, then why should it slow down?

decrease (4 students):

1. In outer space the gravity is heavier.
2. the object has nothing pusing it along so it will avenchually slow down unless it is on a hill
3. if there are no forces on the object, the object will just decreaese the speed it was going.
4. if it slows   down it would become slow.

increase (0 students):

Effect of an Impulse on Speed and Direction

move with the speed and direction of the impulse (0 students):

go with whichever is bigger (the impulse or the original speed) (1 student):

1. It depends on how big the object is and how big the person or whoevers hitting it.

use a combination of both (6 students):

1. i think if the first person hits it really hard and then a second person hits it harder it will probably spin out of control in aknew direction
2. the ball would go at the kicks speed untill it gets to sarah's soft kick then it would vear off
3. I think if an object is already moving the impulse will add to it even if the impulse is bigger because the object already had some velocity.
4. it gets more speed when they combine, if they don't it will go slower.
5. it would combine by going together like another way.
6. it's true that the larger one has more control over the direction, however there's still another amount of impulse/velocity from the other one.

Mass and the Effect of a Force

lighter objects change more (5 students):

1. a lighter object changes because if something hits it will go faster
2. the lighter objects are easier to kick and so they move faster.
3. I said befor that heavie balls change more and the heavie ball went faster so this goe along with my idea
4. a heavier object needs a bigger push to change its velocity.
5. if a bully pushes someone without much mass, they would go farther than someone with more mass because the the person with the most mass could overpower the force of the push.

heavier objects change more (0 students):

all objects have the same velocity change (2 students):

1. the lighter one will catch up to the heavier one eventually
2. if noe is heavier than one of the other sometimes they would go the same speed.

Mass and the Force of Gravity

lighter objects get a bigger pull (0 students):

heavier objects get a bigger pull (7 students):

1. since heavier objects are harder to lift I think gravity also has a harder time pulling it
2. just because
3. gravitie tends to pull harder on something that is heavier because its weight is puled along with the force of gravetie
4. I don't think this is true, but it will make the program behave the way I want it to.
5. on a heavier object gravity will pull harder so that it wont go that fast.
6. it would get a bigger pull than the ligher one.
7. the earth has a gravitational pull (unlike space), and it just pulls the heavier things down more.

all objects get the same pull (0 students):

Effect of Gravity on Velocity

give a pull to all objects, regardless of their motion (5 students):

1. Gravity is always pulling regardless of the objects speed or direction
2. It depends on how hard you are throwing it, if you are throwing it really hard then the gravity gives it a smaller pull, if you are throwing it really light then the gravity gives it a bigger pull.
3. gravitie always gives pulls on an object regardless of upward or down word motion
4. gravity is always pulling the same on all objects, but the force that threw them determines when you see gravity affect them.
5. wherever you are on this earth, it will have a gravitational pull, even on a plane up in the air.

give a pull to all objects, except those going up (2 students):

1. once I threw a baseball in my back yard and it went up, but gravity didn't pull it until the ball went down, and so the ball won't go twice as far as you want it to.
2. when it gos up it pulls more why it is going up.

give a single pull to objects that are stopped (or going sideways) (0 students):

Appendix D

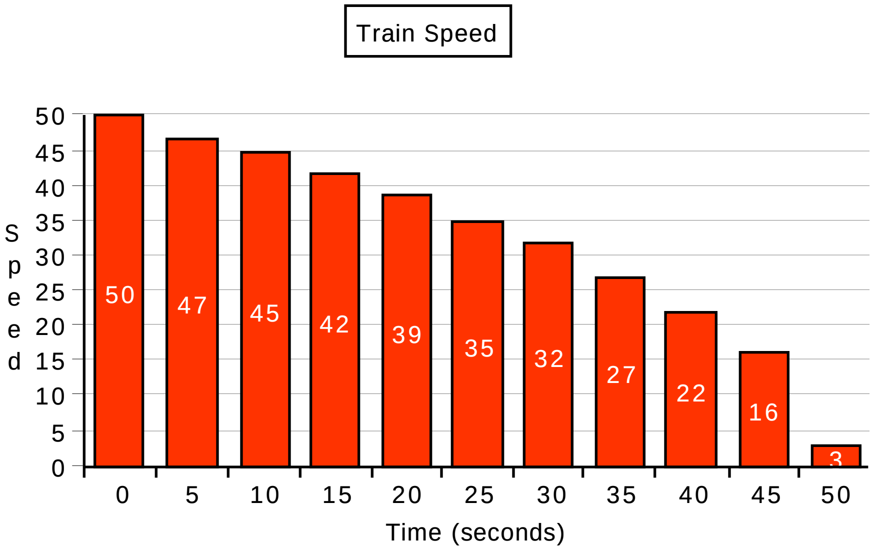
Contextual Concept Test

Some Questions About Force and Motion

Question 1.1 [CCT$_{\text{less familiar}}$][5]

A train is going 50 miles per hour when the conductor realizes that there's a car stalled on the tracks ahead. She turns off the engine and locks the brakes, which stops the wheels from turning. Now the train is skidding down the tracks with sparks flying in all directions. How do you think the train's speed will change as it skids along the tracks?

a)[initial 2][6] The train won't slow down very much at first, but then it will slow down more and more until it comes to a stop all of a sudden:



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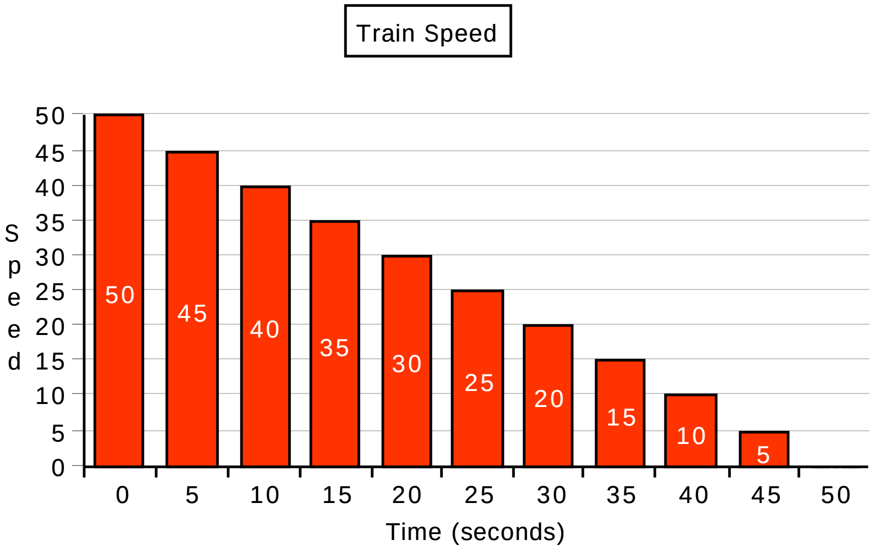
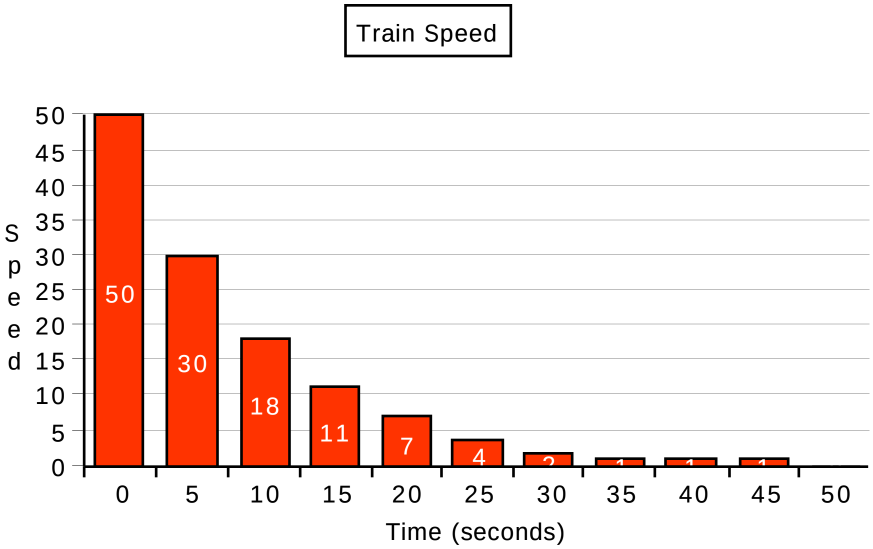
[5] These notes indicate whether a question was from the more familiar, simulated context (CCT$_{\text{familiar}}$) or the less familiar, non-simulated context (CCT$_{\text{less familiar}}$), and were not included in the students' copy of the test.

[6] These notes give the total number of students (out of 7) who chose each answer, both initially and (for CCT$_{\text{familiar}}$) after they had a chance to run a simulation using their Model Design selection.

b)[initial 2] The train will slow down gradually until it comes to a stop:

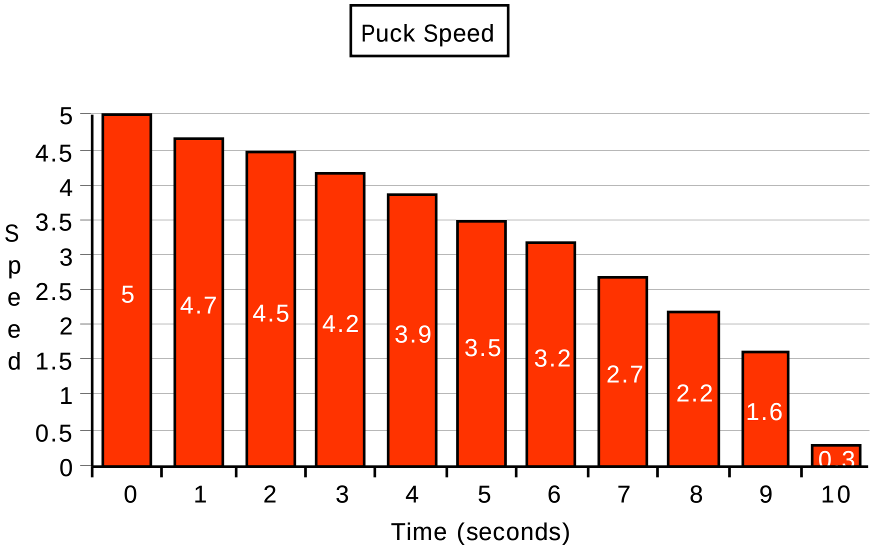


c) [initial 3] The train will slow down a lot right away, but then it will slow down less and less:

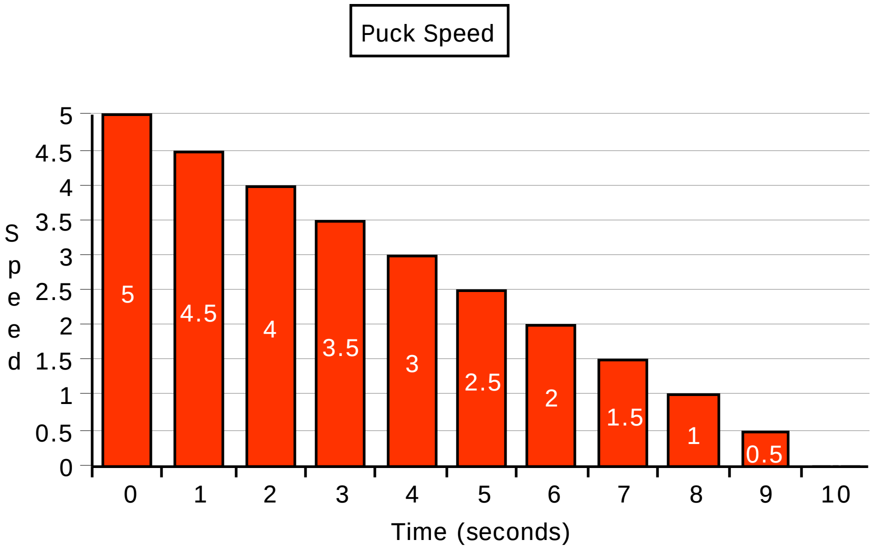


Question 1.2 [CCT$_{\text{familiar}}$]
Kelly slides a hockey puck across the ice and carefully measures its speed after she lets go. How do you think the puck's speed will change as it slows down?

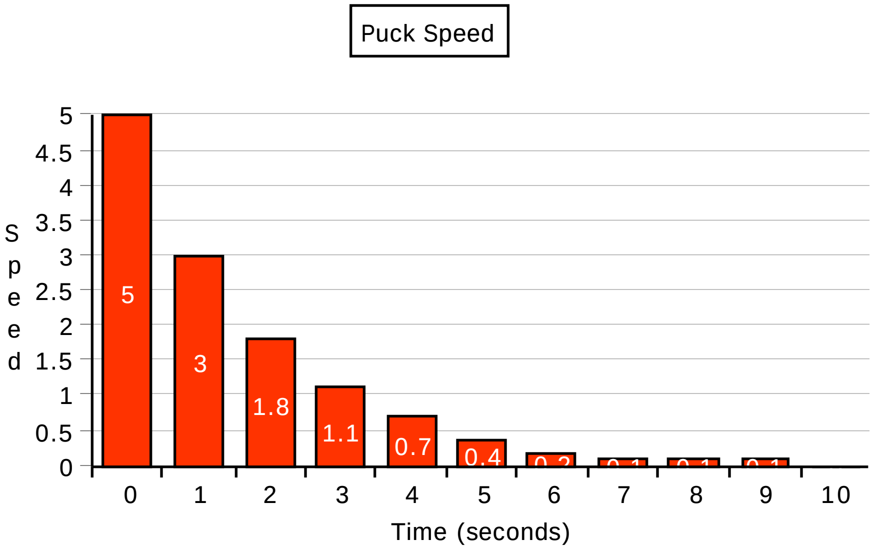
a)[initial 1, revised 2] The puck won't slow down very much at first, but then it will slow down more and more until it comes to a stop all of a sudden:



b)[initial 4, revised 3] The puck will slow down gradually until it comes to a stop:



c) [initial 2, revised 2] The puck will slow down a lot right away, but then it will slow down less and less:



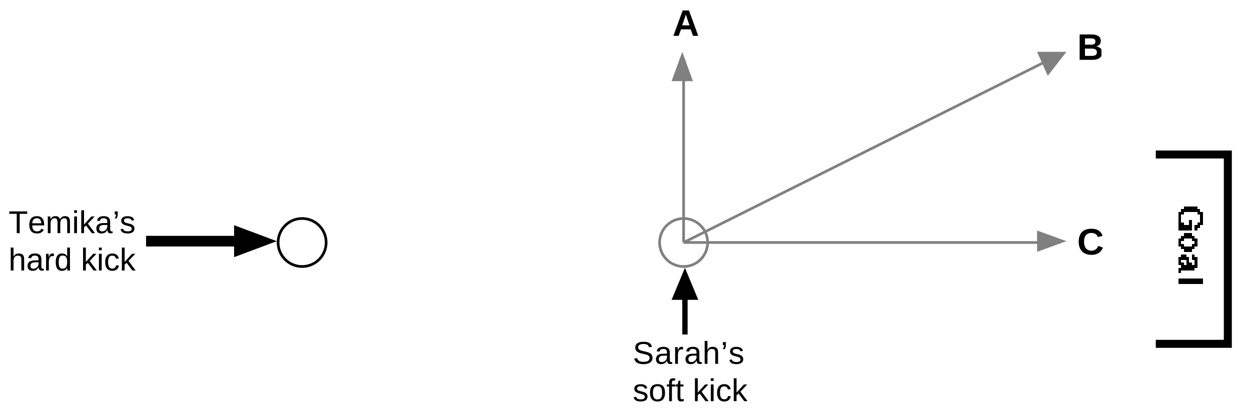
Question 2.1 [$\text{CCT}_{\text{less familiar}}$]
Now imagine that Kelly covers the hockey puck and the surface of the ice with a special super-slippery oil. It might not actually be possible to do it this way, but imagine that she somehow **removes all of the friction from her experiment**. What will happen to the puck after she lets go of it?

a)[initial 0] It will still slow down.
b)[initial 5] It will keep going at the same speed until it hits the other side.
c) [initial 2] It will speed up as it moves along.

Question 2.2 [$\text{CCT}_{\text{familiar}}$]
Imagine that a spaceship is coasting along in deep space with its engines off. It is not near any planets or other outside forces. What will be true about the speed of the spaceship as it moves along?

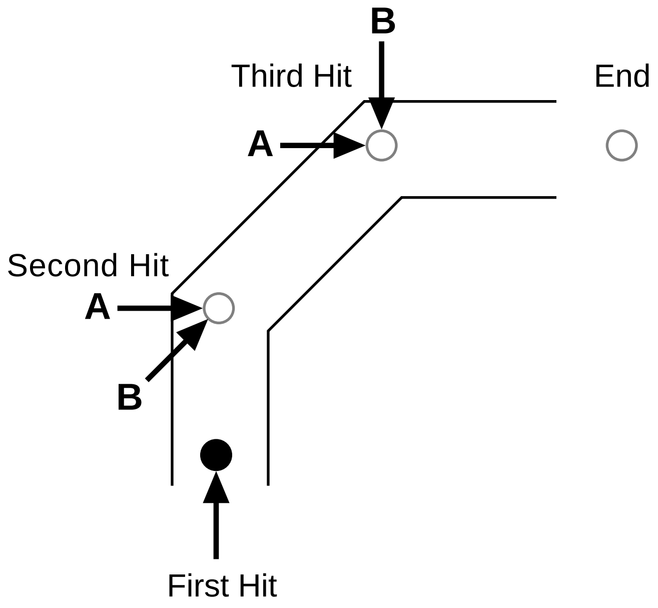
a)[initial 3, revised 4] It will slow down.
b)[initial 4, revised 3] It will keep going at the same speed.
c) [initial 0, revised 0] It will speed up.

Question 3.1 [CCT$_{\text{familiar}}$]
Suppose that Temika kicks a soccer ball really hard toward the goal. As the ball passes by Sarah, she gives it a kick to the side, but only half as strong as Temika's kick. Circle the letter showing the direction the ball will go after Sarah kicks it:



[a) initial 1, revised 0; b) initial 5, revised 6; c) initial 1, revised 1]

Question 3.2 [CCT$_{\text{less familiar}}$]
Suppose that you and your friends are trying to get an ice hockey puck to travel along the track below. At the start of the track, the first person hits it in the direction shown. Circle the letter showing the direction that the second and third person should hit the puck **so that it never touches the sides of the track**. Assume that the ice is super slippery so there's no friction at all.



[Second Hit: a) initial 0; b) initial 7]
[Third Hit: a) initial 7; b) initial 0]

Question 4.1 [$\text{CCT}_{\text{familiar}}$]
Imagine two balls resting on a smooth floor. The balls are exactly the same except that one is four times as heavy as the other one. Now suppose that you give the same sized kick to both balls at the same time. After you kick the balls, what can be said about their speeds?

a)[initial 7, revised 6] The lighter one will be going faster.
b)[initial 0, revised 0] The heavier one will be going faster.
c) [initial 0, revised 1] Both balls will have the same speed.

Question 4.2 [$\text{CCT}_{\text{less familiar}}$]
Suppose you have two shopping carts, one full of light stuff (like bread and cereal) and the other full of heavy stuff (like juice and canned foods). If the two carts are stopped and then you give the same sized push to both, what can be said about their speeds?

a)[initial 4] The lighter one will be going faster.
b)[initial 3] The heavier one will be going faster.
c) [initial 0] Both carts will have the same speed.

Question 5.1 [$\text{CCT}_{\text{familiar}}$-related simulation: different mass objects dropped from same height]
Which does gravity pull harder on, a soccer ball or a bowling ball?

a)[initial 0, revised 0] the soccer ball
b)[initial 6, revised 6] the bowling ball
c) [initial 1, revised 1] gravity pulls the same amount on both

Question 5.2 [$\text{CCT}_{\text{less familiar}}$]
Suppose you take a light shopping cart and a heavy shopping cart to the top of a steep hill. Which one will gravity pull harder on?

a)[initial 1] the lighter cart
b)[initial 5] the heavier cart
c) [initial 1] gravity pulls the same amount on both

Question 6.1 [$\text{CCT}_{\text{familiar}}$]
Tom drops a ball and carefully measures its speed as it falls. Just before the ball hits the ground its speed is 20 feet per second. Suppose that he drops the same ball again, but this time from twice as high. How fast will the ball be moving just before it hits the ground?

a)[initial 0, revised 0] 20 feet per second
b)[initial 7, revised 7] faster than 20 feet per second

Question 6.2 [$\text{CCT}_{\text{less familiar}}$]
Imagine you're jumping off a springy diving board into the pool. Do you think that the height of your bounce has anything to do with the speed that you're going when you finally hit the water?

a)[initial 1] No. You're going the same speed no matter how high you bounce.
b)[initial 6] Yes. The higher you bounce, the faster you're going when you hit the water.

Question 7.1 [$\text{CCT}_{\text{familiar}}$]
Suppose you throw a ball straight upward. When does gravity begin to affect its motion?

a)[initial 4, revised 4] as soon as it leaves your hand
b)[initial 3, revised 3] as soon as it stops going upward

Question 7.2 [$\text{CCT}_{\text{less familiar}}$]
Imagine you're back on the diving board at the pool and bouncing as high as you possibly can off the board before you jump in. When does gravity begin to affect you?

a)[initial 4] Gravity affects you during the entire jump.
b)[initial 3] Gravity begins to affect you as soon as you come to the top of your jump.

Appendix E

Interview Protocol

Introduction

I'm going to be asking you a bunch of questions about how objects (like cars, people, basketballs, etc.) move and why they do things like slow down or speed up. You've had a lot of everyday experience with moving objects, and it's your personal experience that I'm interested in. You don't need to worry about getting the right answer or remembering something your teacher said. I just want you to do your best to explain what **you** think. As you can see, I'm videotaping this interview, so it's not just the answers you pick, but your explanations of why you picked them that matter the most.

The interview will last less than an hour, but it will require you to do a lot of hard thinking. Don't worry, though. We'll can take some short breaks if you get tired. Just hang in there, do your best, and remember that you're not only teaching me how kids learn - **you're also getting paid for it!**

MD Contextual Concept Test

I'm going to give you a series of written questions. Try to imagine the situation described in the question and pick the answer that makes the most sense to you. Try hard to explain what you're thinking about as you make your decision.

Here's the first question [CCT-1.1]. Again, tell me what your thinking about as you try to solve the problem.

Here's the next question [CCT-1.2].

ThinkerTools Software Discussion

Now we're going to do something very different. We're going to use a computer program called ThinkerTools that your whole class will be using later this year (since you're getting to use it first, you'll be the computer expert later!) This kind of program is called simulation software, because it tries to simulate situations like the ones in the questions I've been asking you. You can do experiments with ThinkerTools like dropping balls, and then collect very accurate measurements.

Here's how ThinkerTools simulates a ball bouncing down a hill [TTA-0a].

Here's another simulation. This is supposed to be a car speeding up from a stop sign [TTA-0b].

However, computer programs like ThinkerTools will only simulate the world correctly if they have been programmed correctly, something you're going to help me with. ThinkerTools is going to ask you some questions about which rules it should follow to simulate the real world as accurately as possible.

Computer rules need to be very specific, so there are a couple of technical terms you need to know first:

timestep	ThinkerTools simulates motion by letting a very small amount of time go by and then trying to figure out where all of the objects would be at the end of that time. Since each timestep is very short, it looks like objects are moving smoothly. Actually, though, the program is just moving each object a little bit at the end of each timestep. To demonstrate this idea, I have a movie flipbook movie of the experiment I just showed you. Suppose that your rule is that the dot should speed up a little bit during each timestep. ThinkerTools would simulate this by moving the dot a little bit during the first timestep, then mor and more so that the dot moves a large distance during the last timestep. [Use flipbook movie to demonstrate timesteps and amount of movement during each.]
impulse	This is just the way ThinkerTools simulates a force that acts for a very short time like a hit or a kick.
velocity	You can think of this as another name for the speed of an object. It actually stands for both the object's speed and its direction, but you don't need to worry about the difference too much.
mass	You can think of this as the weight of an object, since on earth mass and weight are the same thing.

Do you have any questions about any of these technical terms? If you forget what any of them mean later, just ask. I want you to understand the questions ThinkerTools will be asking so that you can do your best to answer them.

Model Design Questions

[ThinkerTools should be launched and running with an essentially random set of Model Design options (2nd option selected on each page?) As each MD page is selected, click on the last option and then back to the 2nd option so that the Justify Your Answer dialog always appears in response to the Done button.]

Here's the first question [MD-1]. Since ThinkerTools simulates the world one timestep at a time, it needs to know what sliding friction should do to an object during each timestep. Pick the answer that makes the most sense and then try to explain to me why you think your rule is the correct one.

[Let student click on MD-1 option, then click the Done button. When the Justify Your Answer dialog appears, have them type a summarized justification (or type it for them).]

[Repeat the above with CCT-2.1 & 2.2, MD-2, CCT-3.1 & 3.1, MD-3, CCT-4.2 & 4.2, MD-4, CCT-5.1 & 5.2, MD-5, CCT-6.1, 6.2, 7.1, & 7.2, and MD-6, using the following abbreviated protocol:]

[Save the Model Design file with the student's name (e.g., "Sophia 1").]

ThinkerTools Simulation Discussion

Since you've answered all of its questions, ThinkerTools now knows how to simulate objects in motion. We're going to use the program to simulate a couple of situations, and I want you to tell me whether you think it's simulating them correctly.

ThinkerTools Experiments

Here's how the first experiment looks in the ThinkerTools program [TTA-1].

First let's review what you thought might happen in this situation [CCT-1.2].

Now let's review how you answered the ThinkerTools question about how it should simulate things like this [MD-1].

Now let's see if ThinkerTools simulates the experiment correctly. This is supposed to be a hockey puck on ice. We're looking straight down on it from above the ice rink. This is called a DataCross, and it shows the speed and direction of the puck. Press the F key once to store up an impulse and then press the space bar to begin the simulation. This is supposed to simulate hitting the puck with a hockey stick.

[Have student follow directions to apply a single impulse.]

If you wait long enough, the simulation will reset itself. We can also reset it by selecting Reset from the Simulation menu. This time let's store up two impulses and then release them. This is supposed to simulate hitting the puck twice as hard.

[Have student follow directions to apply and release two impulses.]

Analysis of Experimental Results

What do you think about the simulation? Does it look correct? [If not, allow them to revise their CCT and/or MD choices:]

First let's reconsider what you thought might happen in this situation [CCT-1.2].

Now let's reconsider how you answered the ThinkerTools question about how it should simulate things like this [MD-1].

Rest of ThinkerTools Experiments

Here’s the second experiment [TTA-2]. This is supposed to be an alien spaceship coasting along in deep space with its engines off. It’s not near any planets or outside forces. Since there’s no friction in space, we’ve turned it off in the simulation. Press the space bar to see what happens to the spaceship’s motion as it coasts through space.

[Repeat Analysis of Experimental Results described above.]

Here’s the third experiment [TTA-3]. This is supposed to be a soccer ball about to be kicked by Temika toward the goal. We’re looking straight down on the soccer field from above and this is the goal. Press the F key twice to store up Temika’s hard kick toward the goal. I’ll press the space bar to begin the simulation, and then when the ball gets to where Sarah is, you press the E key once to simulate her soft kick to the side. Are you ready?

[Repeat Analysis of Experimental Results described above.]

Here’s the fourth experiment [TTA-4]. These are supposed to be two balls resting on a smooth floor. The light blue ball has a mass of 1, and the dark blue ball has a mass of 4. We’re looking straight down at the floor from above. Press the F key once to store up an impulse that will be applied equally to both balls (sort of like kicking them both at the same time), and then press the space bar to begin the simulation.

[Repeat Analysis of Experimental Results described above.]

Here’s the fifth experiment [TTA-5]. It’s not exactly the same as the question I asked you, but most people think it’s related. These are supposed to be two balls held above the floor, which is that green line at the bottom of the screen. The light blue ball has a mass of 1, and the dark blue ball has a mass of 4. Press the space bar to let go of the balls so that they can drop to the floor.

[Repeat Analysis of Experimental Results described above.]

Here’s the sixth experiment [TTA-6]. These are supposed to be two balls held above the floor, which is that green line at the bottom of the screen. The red ball is twice as high off the floor as the blue ball. Press the space bar to let go of the balls so that they can drop to the floor.

[Repeat Analysis of Experimental Results described above.]

Here’s the last experiment [TTA-7]. This is supposed to be a ball about to be thrown upward. Press the space bar to begin the simulation.

[Repeat Analysis of Experimental Results described above.]

[Save the Model Design file (e.g., “Sophia 2”).]