Published in Proceedings of the International Conference on Computers in Education 2003, (eds. Chee, Y. S., N. Law, K. T. Lee, & D. Suthers), Hong Kong, pp. 921–929. AACE. (CD–ROM ISBN: 1–880094–51–7)

Design and evaluation of computer tools for building process and causal models: A case study

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Abstract: There has been renewed interest in model-based learning in science education focusing on models of phenomena, rather than on abstract concepts. This paper reports the design of two modeling tools—process-model and causal-model building tools—in a computer-supported learning environment and a case study of a pair of students collaboratively building models of falling objects with the help of the tools. Based on analysis of ways to narrow the gulf between everyday reasoning and scientific reasoning, it is argued that building both localized process models and global causal models provides effective learning experiences for students. The case study presents evidence that model-building can help students externalize their thinking and foster critical reflection and deep understanding of scientific principles.

1 Introduction

It is now widely acknowledged that learning science involves deep conceptual understanding of scientific principles that are often in conflict with students' intuitive understanding. Accordingly, the "Learning as conceptual change" approach holds sway in science education these days. The emphasis of recent research in this field is on students' understanding of abstract concepts (e.g., Martin *et al*., 2000). Science learning is approached in terms of grasping the conceptual structures of a domain consisting of concepts and their relations. Often this conceptual structure is organized in a hierarchical tree based on a certain ontological classification scheme, and researchers can compare students' initial and final conceptual structures (with experts' conceptual structure as reference point) and characterize the change as "weak" or "strong". For example, Reiner *et al.* (2000) argue that radical conceptual change needs a change across ontological categories, such as the scientific concept of force changing from the category of substance or property of objects to relation between objects.

However, the focus on abstract, high-level concepts is based on a syntactical view of science and does not pay adequate attention to the role of models and exemplars in thinking scientifically. A model, such as a map or diagram, is a structural or functional analog of phenomena or states of affairs in the world. A model builds a semantic relation between abstract theory and phenomena, thus helping us build a rich, embodied understanding of theory (Giere, 1999). "The practice of normal science depends on the ability, acquired from exemplars, to group objects and situations into similarity sets which are primitive in the sense that the grouping is done without an answer to the question, 'Similar with respect to what?'" (Kuhn, 1970). In other words, abstract concepts in themselves do not tell us how to apply them in different situations. Hence, even if students know that force is a relation, this does not tell them how to identify different kinds of forces and what models to use in a certain situation. There are no explicit rules for that. Rather, scientific practice is learned implicitly from exemplars showing how to build models of phenomena. Models are widely used in the classroom ranging from scale models to mathematical models. But in research circles they have not received the attention they deserve.

Model-based learning promotes constructivist and inquiry-based learning by engaging students in building models of real world phenomena. However, model building is hard for students, attested to by the fact that they rarely explicitly build models of phenomena in real life although they encounter them from moment to moment. The real world is a complex place with many things happening quickly and simultaneously, and students lack the necessary conceptual and material tools to acquire scientific understanding of phenomena. Computer-supported learning environments offer great promise in providing idealized yet realistic simulation environments and powerful yet friendly tools to scaffold student inquiry (see, for example, Chee & Hooi,

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2002). We have developed a model building environment for the phenomena of falling objects, and, specifically, two modeling tools are designed for building process and causal models. We argue that building both process and causal models provides effective learning experiences for students.

In what follows, we first briefly examine the relevant literature, introduce the phenomena under study and present the design rationale of our learning environment, highlighting building tools for process and causal models. A case study of a pair of students collaboratively building and explaining models with the help of the tools is presented. We discuss the results and draw conclusions in the last section.

2 Inscriptions, models, and computer tools: an overview

Creating external representations (also called inscriptions) is fundamental in both research and everyday life. "Inscription involves deliberately selecting and amplifying particular attributes for further study—in effect, transforming aspects of the world into data" (Lehrer & Schauble, 2000). It is fundamentally social in nature as it creates a common social context by symbolizing, objectifying and organizing internal fuzzy thinking. To make social interaction effective, inscriptions are governed by social norms that emphasize communication, clarity of expression, and orientation to inscriptions as resources for thinking (Lehrer & Schauble, 2000).

Models, as an important kind of representations, can be classified in different ways. For example, based on degree of abstractness of the similarity between models and what they represent, models can be classified as scale models (literal similarity), maps and diagrams, and analogy (structural similarity). Here, we group models into process and causal models based on whether the models are temporal or not. Process models are dynamic and temporal models that step through time and describe the moment-to-moment change of an event. They stand out as very useful in both simulating natural events in research and characterizing people's natural understanding of events and mechanical devices (Gentner & Stevens, 1983). People invent stories and narratives to conceptualize events in the world, and they also apply causal principles to predict and explain the moment-to-moment change in the flow of events. Contrary to process models that describe local change, causal models establish the global causal structure of a situation by building causal relationships between relevant factors.

Computers hold promise as cognitive tools to support, guide, and extend the thinking processes of their users (Lajoie, 2000). Computers are especially good at guiding and structuring inscription creation and discussion by virtue of their symbolic nature and multimedia richness. Modeling tools, the focus of this paper, are cognitive tools for model building. As a typical example, *ThinkerTools* (White, 1998) provides a modeling environment guiding students to step through time and generalize the causal principles of the events involved.

3 Design of learning environment

3.1 Analysis of phenomena and subjects' explanations

To design the learning environment, a preliminary step is to carefully analyze students' explanations of everyday phenomena, here phenomena of falling objects. Although students see objects falling everyday and they have rich knowledge of it, it is only in science class that they begin to puzzle about it: why do a feather and a coin fall at the same speed in a vacuum, and why is this explained in terms of gravity? The phenomena and the interpretative framework are both so different from students' everyday experience that the teacher can only hope that a motivated student would try to resolve the discrepancies between everyday thinking and scientific reasoning on their own. As we know, this rarely happens. To further probe their understanding, students are introduced to various phenomena of falling objects in a Predict-Experiment-Explain fashion. For example, given two objects falling through air (an elephant and a feather, an iron ball and a wooden ball, etc.), students are asked to predict and explain which would fall faster and why. Table 1 presents a classification of the phenomena of falling objects and their explanations, including both scientific explanations and the subjects' typical explanations (subject's protocols are quoted). As the falling process is complex and subtle, we present data and graphs of two objects' falling processes (object A and object B) to better illustrate the idea (see Fig. 1). The speed of both objects starts from zero and increases, and the acceleration of both objects starts from the gravitational constant (9.8) and decreases, but the rates at which their speed increases and their acceleration decreases are different. Object B's acceleration decreases at faster rate than object A, so at any moment its acceleration is smaller and its speed will increase at slower rate, leading to smaller average speed (see Fig. 1). The reason for this is that object B has a larger ratio of air resistance to mass and correspondingly its acceleration will decrease at a faster rate (see Table 1).

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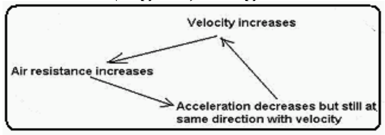
<table>
<tr><th></th><th colspan="2">One object
(Focus: describing and explaining falling process)</th><th>Two objects
(Focus: explaining speed difference)</th></tr>
<tr><td rowspan="2">Thro-ugh air</td><td>Scientific explanation</td><td>$a=(mg-Fr)/m=g-Fr/m$


Finally acceleration decreases to zero and speed reaches constant (terminal speed)</td><td>$a=(mg-Fr)/m=g-Fr/m$
For object with higher ratio of air resistance to mass, its acceleration will decrease more quickly and its speed will increase more slowly, leading to slower average speed and longer time to fall to ground.</td></tr>
<tr><td>Subject's explanation</td><td>1. For describing falling process: "This object is falling fast"
2. For explaining falling process: "Falling is due to downward pull of gravity"</td><td>Exemplar situations and explanations are:
1: Two pieces of paper with one crumpled: "The one that crumples falls faster. There is more resistance"
2: Two pieces of styrofoam with one's surface area twice the other: subjects explained why they fall at same speed by cutting the larger one into two.

</td></tr>
<tr><td rowspan="2">In a Vac-uum</td><td>Scientific explanation</td><td>$a=mg/m=g$, so object's speed increases at constant rate</td><td>As speed of both objects increases at constant rate, they fall at the same speed.</td></tr>
<tr><td>Subject's explanation</td><td>"Gravitational pull will give the same acceleration"</td><td>"If they start at zero and acceleration is the same, they move at the same speed"</td></tr>
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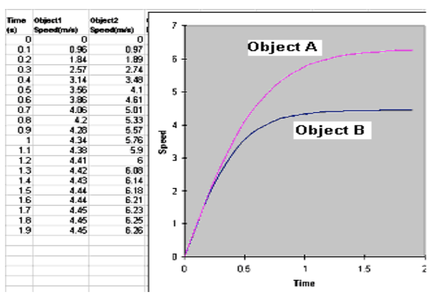
Table 1: Classification and explanations for phenomena of falling objects
(*m* for *mass*, *g* for *gravity, a* for *acceleration, Fr* for *Force of Air Resistance*)



Time (s)	Object1 Speed(m/s)	Object2 Speed(m/s)
0	0	0
0.1	0.96	0.97
0.2	1.84	1.89
0.3	2.57	2.74
0.4	3.14	3.48
0.5	3.56	4.1
0.6	3.86	4.61
0.7	4.06	5.01
0.8	4.2	5.33
0.9	4.28	5.57
1	4.34	5.76
1.1	4.38	5.9
1.2	4.41	6
1.3	4.42	6.08
1.4	4.43	6.14
1.5	4.44	6.18
1.6	4.44	6.21
1.7	4.45	6.23
1.8	4.45	6.25
1.9	4.45	6.26

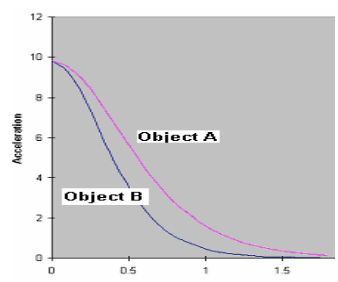


Figure 1: Data and graphs of speed (left) and acceleration (right) for two objects.

Table 1 provides some data for us to explore the difference between subjects' explanations and scientific explanations. For the phenomenon of falling in a vacuum, subjects' explanations are roughly consonant with scientific explanations. But for phenomenon of falling through air, subjects fall back on everyday reasoning. Their compartmentalization of scientific reasoning to alien phenomena is mainly due to the following reasons:

- People's everyday concepts of speed and acceleration are global and rough due to perceptual insensitivities, as seen from statements such as "This object is falling slowly" or "This object is speeding." In contrast, velocity and acceleration in Newtonian mechanics are accurate concepts localized in specific time and space, such as "The object's velocity at time T and location S is 3 m/s"
- The well noted conception in conceptual change research, "*Speed being proportional to force*" (Disessa, 1993), provides basis for subjects' explanation of objects' speed difference in terms of different weight or air resistance (see Table 1). This conception, combined with subjects' everyday concept of speed, produces an explanation natural to subjects: they would just regard speed of both objects as constant and use different forces on two objects to explain their speed difference.

To appreciate the broader implications, we may ask: what essential knowledge is involved in explaining the phenomena scientifically? Basically it involves the interaction between force, acceleration, and velocity, which is all Newton's Second law ($F=ma$) is about. What students encounter in the classroom are simple situations where acceleration and total force are constant and normally in the same direction (e.g., sliding on an inclined plane), whereas falling through air involves moment-to-moment interaction between force, acceleration, and velocity and offers an opportunity for deeply probing students' understanding of Newton's laws.

3.2 Design of modeling tools

Design of the learning environment is aimed at narrowing the gulf between subjects' everyday reasoning and scientific reasoning. Firstly, simulations and related data and graphs should be provided, as the global character of students' concept of speed makes them unable to appreciate the subtlety of the falling process. Secondly, modeling tools are needed for students to build models based on data. To understand both the phenomena of falling objects and Newton's laws, we argue that students should be able to

- Construct both process and causal models of the phenomena. On one hand, only if a student can describe the falling process step by step can we claim that he has understood the phenomena. On the other hand, if students can only explain falling process of one object, they fail to see the global character of the process such as how the object's surface area affects its falling time. A causal model establishes such global causal relationships by comparing different objects' falling processes.
- Check and explain these models. Just as science involves both phenomenal descriptions and underlying mechanisms, or "what is the case" and "why it is the case", we engage students in explaining the models with scientific principles, here Newton's laws. Newton's laws are used to explain both models but serve different roles: to explain local change in process models and global patterns in causal models.

3.2.1 Process-model building tool

Our process-model building tool aims to deepen students' understanding of Newton's laws. As stated in section 3.1, a significant hurdle is students' conception of "*Speed being proportional to force.*" To overcome this conception, a cognitive conflict strategy is adopted. The above conception will not hold when force and speed are in opposite direction, as in the case when a car's brake is pushed: the force of friction is backward, but the car will go forward for some time due to inertia. Here we choose the phenomenon of a falling skydiver, as its total force and speed are in opposite direction after the parachute is opened. Data and graph of the falling process are shown in Figure 2(a). After some time falling, the skydiver reaches terminal speed one (see Table 1 for explanation of the process). After a moment he opens the parachute and air resistance suddenly increases greatly, causing deceleration. Finally the skydiver reaches terminal speed two (see Fig. 2(b) for the process).

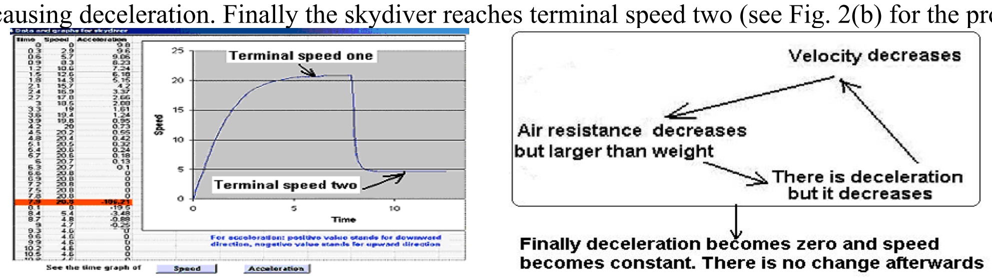


Figure 2 (a): Data and graph of falling skydiver (left) **(b):** process of reaching terminal speed two (right)

The process-model building tool is divided into three parts: (1) *Explore simulation* for exploring simulation of a falling skydiver, (2) *Build process model* for describing the process (see Fig. 3 for the interface), and (3) *Refine your model* for model checking and explanation. The modeling tool structures and guides model building by specifying what factors to look at and what features to notice for a specific factor. The user can build the model by selecting from lists of predefined values for a specific factor, and Figure 3 shows a process model built by subjects and their choice for velocity in the interval between 1.2 and 6.6 seconds. As process models are temporal, the most important thing in building a process model is how to divide the process into distinct time intervals. The grain size of the intervals is determined by the criterion that each interval should represent a distinct change pattern of relevant factors. Here, three factors (velocity, acceleration, and air resistance) are involved, and Table 2 shows the relationships and constraints between them. As changes of acceleration and air resistance are finally reflected in change of velocity, an interval is defined as a time period when the velocity's change trend (increasing or decreasing) and change rate (increasing or decreasing) are different from nearby intervals. Table 2 also provides clues for us to specify which feature of a specific factor should be included in the model by judging this feature's influence on other factors. For example, acceleration is influenced greatly by whether air resistance is larger than weight, so this is included in the model as a feature of air resistance.

Velocity & Acceleration	Acceleration is defined as velocity's change rate over time.
Air Resistance & Acceleration	If resistance is less than weight, acceleration is downward and will decrease if resistance increases. Vice versa if resistance is larger than weight.
Velocity & Air Resistance	Air Resistance is proportional to velocity.

Table 2: Relationships and constraints between velocity, acceleration, and air resistance

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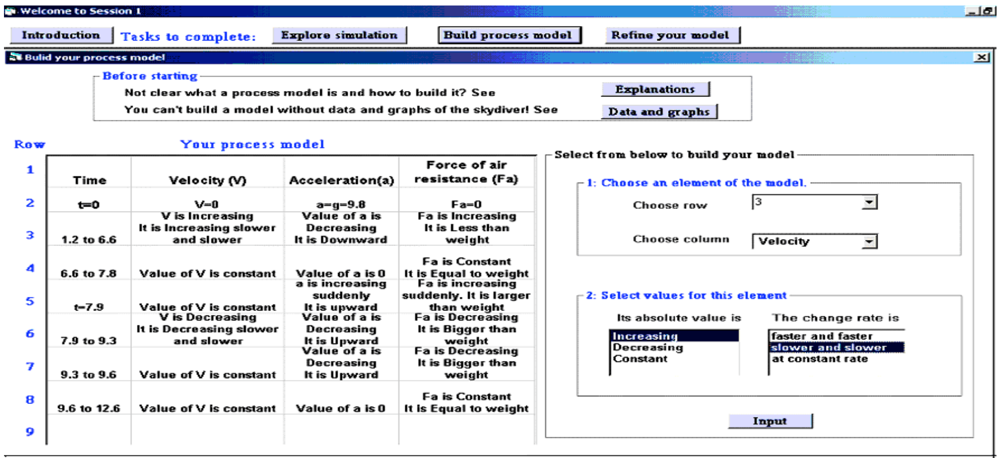

Figure 3: Process-model building tool screenshot.

The second part, *Build process model*, engages students in making explicit the change process of air resistance, acceleration, and velocity in a qualitative way. It is more descriptive in the sense that students can build the model by just reading from data and graphs (but note that students must infer how air resistance changes as there is no graph and data for air resistance). The third part, *Refine your model*, is explanatory, as students are required to use Newton's laws to both check and explain their process models. Specifically, they are asked to check the consistencies both between the process model and their intuitive knowledge and between different parts of the process models. For example, if in an interval velocity is constant but acceleration is not zero, this would violate Newton's laws and students are asked to resolve the discrepancy.

3.2.2 Causal-model building tool

In school laboratory sessions students normally build causal models by performing controlled experiments to ascertain regularities from data. However, this way of learning science hardly captures what is really hard in scientific research: conjecturing explanatory theory to explain phenomena. Hence, if a student has ascertained from experiment that a pendulum's period is affected by its string's length, he gains little from this fact. If he can explain this with Newton's laws, this would be evidence that he has achieved deep understanding. Our causal model building tool aims to foster deep understanding of students beyond discovering regularities from data.

The causal-model building tool is divided into four parts: (1) *Explore simulation*; (2) *Build basic models*; (3) *Build a complete model*; and (4) *Use the model to explain phenomena*. In the first two parts, students perform controlled experiments to find out the causal relationships between object properties and properties of the falling process. The results are summarized in Table 3. In total, three basic models are built and one of them is shown in Figure 4(a). Figure 4(a) and Figure 4(b) show the interface of model building for both basic models and the complete model: the causal factors involved are provided by the system, and students fill in the causal relations by selecting from a list of causal relations (not shown here) such as UpLinear (i.e., positive and linear), Positive, Negative, etc. These relationships are organized in a hierarchical tree in terms of degree of generality with general relations serving as parent node of more specific relations (e.g., *Positive* is parent node of *UpLinear*). Students are required to be as specific and accurate as possible when selecting a causal relation.

		Properties of the falling process		
		Decrease rate of acceleration	Increase rate of velocity	Falling time
Object propertie s	Density(Material): Cork, Wood	Negative	Positive	Negative
	Surface area: Small, Large	Non-causal	Non-causal	Non-causal
	Height: Small, Medium, Large	Negative	Positive	Negative

Table 3: Causal relationships between object properties and properties of falling process

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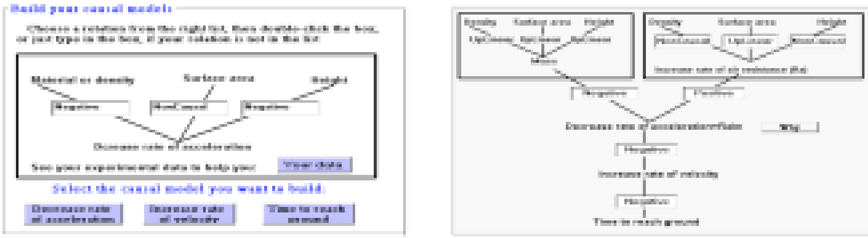

Figure 4 (a): A basic model of falling process (left) **(b):** The complete model for falling process (right)

Broadly, the first two parts (*Explore Simulation* and *Build basic models*) are descriptive in the sense that students may build all the basic models correctly but still do not know why. Indeed, all our subjects find the conclusion that surface area does not affect falling time very unusual, as they think that larger surface area implies larger resistance and slower velocity. The third and fourth parts (*Build a complete model* and *Use the model to explain*) are explanatory: they engage students in building a complete model and using this model to explain phenomena of falling objects. The complete model (Fig. 4(b)) has the following characteristics:

- It has a complex five-layer structure integrating all the causal relationships (see Table 3) together. The structure guides subjects to consider all the relevant factors and their interactions at the same time, fostering systematic thinking and complex chain of reasoning. Moreover, the relationship between a layer and its lower one is not based on data but explained from the relationships between force, acceleration and velocity. For example, the relationship between decrease rate of acceleration and increase rate of velocity is negative (Fig. 4(b)), because if one object's acceleration decreases slower than another, at any moment its acceleration will be larger, so its velocity will increase more quickly.
- The model quite explicitly encourages a *fight* interpretation of the falling process: there is a fight between *Mass* and *Air Resistance* concerning which factor will determine falling speed, and the result is determined by the ratio between them. Specifically, the model makes *Mass* and *Air Resistance* salient by enclosing them with separate rectangles and putting them in the second layer in the five-layer structure (Fig. 4(b)): object properties (first layer) affect them directly and the ratio between them determines *decrease rate of acceleration* (third layer) and finally determines falling time. Under this construal, it is easy to see why surface area does not affect falling time: it affects both *Mass* and *Air Resistance* and its effect cancelled out in the ratio between them. Utilizing experiential *p-prims* such as "fight" and "pull" (Roschelle, 1991) in the design of learning environment is a useful strategy.

4 A case study

We report a case study of a pair of subjects collaboratively interacting with the modeling tools. The case study aims to investigate whether our modeling tools can foster student reflection and deep understanding of scientific principles. As this research is not designed to teach students physics from fresh, we chose subjects who have finished secondary school and have majored in physics. As there are no explicit collaboration tools in the learning environment, we chose subjects who have worked together before to facilitate collaboration. The subjects are Jason and Andy (pseudo names), denoted by J and A. J and A are both boys of 15 years old and have scored B4 and A1 (equivalent to B minus and A plus) respectively in physics in the preliminary O level test (the test for entering Junior College). The learning scenario consists of three sessions, and two of them deal with process model building and causal model building respectively. We use parentheses to explain the situation and alphabet followed by number (e.g., J1) to specify a sentence's order in a subject's protocols in a session.

4.1 Process model checking and explanation

The protocols below occur when subjects were checking their process models. J initiated the discourse by attempting to find patterns from the process models (J18), and this led to A & J collaboratively inventing a new representation to represent the process model they had built. The new representation is quite creative in some respects, such as putting a short arrow on top of a long arrow ( ) to represent the trend of *increasing at slowing rate*. In effect they had re-presented the process model in a form that is easier to understand and handle for them, and that was quite an achievement. Moreover, with the new representation at hand, subject A found out the pattern between acceleration and air resistance (A19, A20) that was quite consonant with our summarization in Table 2, and J attempted to generalize this conclusion to all phenomena of falling objects (J21).

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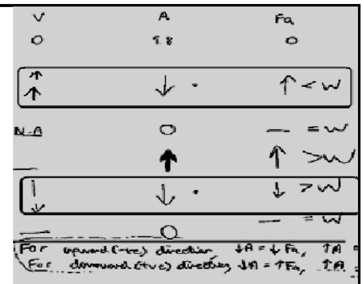
J18	*Come, let's find a pattern. Let's do it now (J begins to write on the paper and the result is shown on the right)*
A19	*Depends on direction. The main thing is these two (the two intervals, enclosed as rectangles on the right figure). When it (acceleration) is downward, these two (air resistance and acceleration) is (in) opposite (direction). When it (acceleration) is upward, these two are the same.*
J19	*What you mean opposite?*
A20	*That means (if acceleration) increasing, (air resistance is) decreasing, (if acceleration is) decreasing, (air resistance is) increasing (A then writes on the bottom of the right figure: "For upward direction, _A=_Fa, _A=_Fa. For downward direction, _A=_Fa, _A=_Fa")*
J20	*Yeah, it is logical. That means from this you can derive any other. . .*
A21	*(Interrupting) Are you sure any other?*
J21	*This is the trend. That means any other fall, you can use this to explain.*



Legend:
Fa: Air resistance *W*: weight
V: Velocity *A*: Acceleration
_: increase _: decrease

Subjects continued to examine the new representation. In this process, J began to wonder why after parachute is opened, velocity decreases when air resistance decreases (J36). This reflects his idea of "Decrease of speed being proportional to resistance" which is quite similar to "Speed being proportional to force". In J37 his reasoning follows a chain from force (here air resistance) to acceleration to velocity, and through this scientific way of reasoning he clarifies confusion of the relationship between air resistance and velocity (J38).

J36	*(Examining the new representation) Wait, I thought only when air resistance increases, the velocity will decrease.*
A35	*Velocity decreases.*
J37	*Air resistance decreases, acceleration decreases. But how velocity decreases? Wait. I know, I know. Although it (air resistance) decreases, right, but it is still bigger than (weight). . . Because its (parachute's) diameter is very big, and it (air resistance) increases suddenly, so even if it (air resistance) is decreasing, but (it is) still bigger than weight.*
A36	*Velocity is decreasing, slower and slower.*
J38	*But still bigger than weight. That means no matter how it (air resistance) decreases, as long as it is bigger than weight, this one (velocity) will decrease. Do you understand?*

In the above two excerpts, subjects have shown evidence of improved understanding of the relationships between force (here air resistance), acceleration, and velocity, and in the latter excerpt they have also resolved contradictions between their intuitive knowledge and the process model. It is worth noting that subjects have created new representations of the process model to facilitate finding patterns from and reasoning with the model. This shows the indispensable role of the modeling tool in facilitating subjects' reasoning process.

4.2 Using causal model to explain phenomena

The following excerpt occurs when subjects were using the complete model (see Fig. 4(b)) to explain two phenomena: falling of elephant and feather, and two pieces of styrofoam with one styrofoam's surface area twice that of the other. In both cases, one object has larger air resistance but also has larger weight, so it is not enough to consider weight or air resistance only and a more systematic approach is needed. In the probing stage happened before building models, A invented an intuitive explanation for the case of two pieces of styrofoam by cutting the larger one into two (see Table 1). However, they failed to find an intuitive explanation for the case of elephant and feather, and they also failed to provide a unifying framework to explain these two phenomena. The complete model (see Fig. 4(b)) provides such a unifying framework. With the model at hand, J explained the former case by regarding the process as a fight between *Mass* and *Air resistance* (J72), and in J73 he offered an explanation of why surface area (what he calls contact area) did not affect falling time but height and density affected falling time, which was quite consonant with explanations in section 3.2.2. In A67, subject A repeated his intuitive explanation. In A68, he adopted the complete model as an explanatory framework and, specifically, he resorted to density difference between elephant and feather to explain their speed difference, and he further used the factor of density to explain why the splitting method cannot work here but works well in the case of two pieces of styrofoam. This distinction between two cases (objects have different densities in the first case and same densities in the second case) would be hard for subjects to see without the model at hand, and they do fail to notice it before. Both A and J show evidence of systematic, scientific reasoning afforded by the causal models. Moreover, the intuitive explanation is not discarded but explained in a unifying framework (A67, A68).

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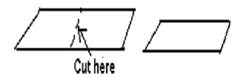
J72	*(Explaining the case of elephant and feather) Yeah! Mass is density times height times surface area, (Elephant's mass is) very big. This one (Elephant's mass) is three increases together (As elephant's density, surface area and height are all larger than that of the feather), three increases! But this side (Air Resistance), right, only has one variable (only surface area affects resistance). This (left) side causes elephant to fall faster, so it is three down. Ok, this (right) side, one up. So it is two down. So these three independent variables contribute to the mass.*
A67	*(Explaining case of two styrofoam) This one (larger one) has double the surface area than this one (smaller one), but this one (larger one) also has double the mass than this one (smaller one), so you split it up, it is the same. It is like two joined up.* 
A68	*(Looking at the model) If only surface area changed, right, it is just like two placed together. But in your elephant and feather, right, density also involves, that means you can not do this (splitting). . .*
J73	*Yeah. Why contact area is non-causal, right, because it affects both (left and right) sides. Whereas why other factors are causal, right, because then they whatever is (are) just affecting this side (Mass, left side), not this side (Air Resistance, right side), because the height and density, it does not (influence air resistance). . . Very clearly, how those variables like height and density can contribute to the change of these factors (falling time and speed) it is through mass, whereas it doesn't affect this side (air resistance) at all.*

5 Conclusions

The case study above shows evidence of the role of our modeling tools in facilitating reflection and deeper understanding of scientific principles. We note, however, tools providing more structured support for reflection and explanation are needed to accommodate larger pools of students (maybe a class). Our modeling tools are also not generic enough. A framework specifying the relationship between situational specifics and model attributes is needed so that authoring tools based on this framework can be built for students to build models for whatever phenomena they are interested in.

Based on our current work and evidence, we conclude that engaging students in building process models and causal models and further explaining these models can foster deeper understanding of both scientific principles and systematic, scientific reasoning. As discussed above, much more work need to be done to fully utilize the advantage offered by model-based and constructivist learning.

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