DESIGNING FOR COGNITIVE COMMUNICATION: EPISTEMIC FIDELITY OR MEDIATING COLLABORATIVE INQUIRY?

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Abstract

This article examines the generalization of the mental model principle to communication of a system of concepts across worldviews. I use an example of an educational simulation designed to teach physics concepts to examine such communication and to illustrate two design perspectives.

Gaps between worldviews prevent students from interpreting displays literally, and thus limit the extent to which communication can be achieved by representing knowledge accurately. Hence, rather than merely representing mental models accurately, designers must focus on supporting communicative practices. I suggest four specific design principles within a mediated collaborative inquiry perspective.

1.0 Introduction

> Intentions are fairly easy to perceive, but frequently do not come about and are not fulfilled. Design is hard to perceive. But it is design and not intention that creates the future. (Boulding, 1985, p. 212)

Software should be designed to support the user's mental model of how the system operates (Young, 1981; Kieras & Bovair, 1984; Tauber & Ackermannn, 1990, 1991; Norman, 1991). For example, a graphic user interface (GUI) desktop helps users learn computer filing systems by supporting a direct-manipulation model analogous to a familiar, physical desktop (Smith, Irby, Kimball, & Verplank, 1982).

This article examines the generalization of the mental model principle to communication of a system of concepts across worldviews. By building a computational model, educators often intend to communicate difficult concepts, enabling students to learn science, mathematics, history or another subject more easily. This generalization extends the original mental model principle in two ways.

First, in the general case, the target knowledge is EMBODIED in computation, but is not necessarily ABOUT a computer system. The GUI desktop is a model of a computer's filing system. In contrast, in the example used in this paper, students learn about the concepts of velocity and acceleration. These concepts are not generally involved in the operation of a computer system.

Second, in the generalized case, learners cannot readily assimilate target knowledge to their current worldview. Thus, whereas the GUI desktop is a natural extension of an office worker's existing model, in the example used in this paper, communication requires that students cross the gap between their view and scientists' view of physics concepts.

Dynamic and visual computer displays offer the possibility of enhancing communication about concepts across worldviews, but also raise a difficult issue: How can computer representations be used to communicate a system of concepts to a student who does not already participate in the expert's worldview? Answering this question requires considering the relation between a designer's intentions and students' learning processes. How are external representations related to the knowledge that students construct?

In one view, external representations denote concepts, constraints, or models that learners seek to decode and internalize (Reddy, 1979). A design is assumed to be superior if the external representation portrays the expert's mental model with high fidelity -- with accuracy and clarity, and without ambiguity or extraneous noise. Henceforth, this approach will be called "Epistemic Fidelity" (Wenger, 1987): It focuses attention on the fidelity of a external display with respect to an expert's mental model.

Using a case study of the "Envisioning Machine" (EM), an educational simulation that is intended to help students learn physics concepts, I will expose the fallacy of assuming that a high fidelity model will lead to appropriate knowledge structures in a learner's head. In fact, students often do not know what to do, where to look, or how to make sense of a visual display in order to internalize external models correctly. Thus, students do not perceive the design in accordance with the designers' intentions.

This is a symptom of the disjunction between newcomer and expert worldviews (Clancey, 1989). In particular, extensive research has documented the depth of the disjunction between science students and professional scientists (Carramazza, McCloskey, & Green, 1981; Halhoun & Hestenes, 1985; McDermott, 1984). The gap between students' and scientists' worldviews is not localized at the level of "concepts" and "misconceptions," but extends throughout the fabric of thinking -- including perception, focus of attention, descriptions of the world, practices of interactions with the world, forms of valid knowledge, and values. Artifacts cannot form a conduit that passes "mental models" across the gap between expert and newcomer worldviews.

In an alternative view, external representations mediate interaction through which learners construct and maintain shared interpretations. External representations can constitute a physical backdrop against which learners coordinate communicative acts so as to increasingly participate in a community's practice of representation use (Lave & Wenger, 1989). Learning occurs through a social process of inquiry (Dewey, 1938) that occurs as students create, negotiate and try out meanings for the activity in which they are engaged. I call this alternative perspective "mediated collaborative inquiry" (Roschelle, 1992a) because it focuses on the role of design as providing a medium that supports communicative practices which enable meanings to be shared.

The mediated collaborative inquiry (MCI) perspective differs from a high fidelity perspective in three major ways.

First, the design goals are different. MCI design focuses on the resolution of ambiguities and differences in interpretation (Roschelle & Clancey, 1992). In contrast, the epistemic fidelity point of view assumes that communication and internalization can be unproblematic if the relationship between the display and the target mental model is made precise.

Second, in the epistemic fidelity view, the main axis of interaction is between the computer and user. In the MCI view, the main axis of interaction is among people, with the computer model providing common ground to act upon and talk about (Teasley & Roschelle, 1993).

Third, whereas the epistemic fidelity view seeks to enable learning by representing knowledge or embodying models, the MCI view seeks to enable learning by supporting communicative practices. This view highlights the importance of designing resources that help people manage the uncertainty of interpretation that inevitably occurs when learners interact with expert representations.

Much has been written about the difference between conventional teaching and collaborative inquiry-based teaching (e.g. Johnson & Johnson, 1987; Slavin, 1990). Herein, I focus on the significance of this change for the design of computer displays. I suggest four specific design principles within a mediated collaborative inquiry perspective:

o Extending engagement with the problematic situation,

o Supporting focus and context,

o Enabling communicative action, and

o Learning by doing .

These directly relate to needs that arise when conversational participants attempt to construct shared meanings that span worldviews.

2.0 The Envisioning Machine

The EM (Roschelle, 1991) is a direct-manipulation graphical simulation of the scientific concepts of velocity and acceleration. It is intended to be a tool for beginning physics students at the level of middle school through first-year university. The EM screen is divided into two windows: the "Observable World" and the "Newtonian World." The Observable World displays a ball (a black circle) and the Newtonian World displays a particle (a white circle). The thin arrow with its base at the particle's center represents the particle's velocity vector. The thick arrow with its base at the velocity's tip represents the particle's acceleration. Students control the simulation using a menu of commands.

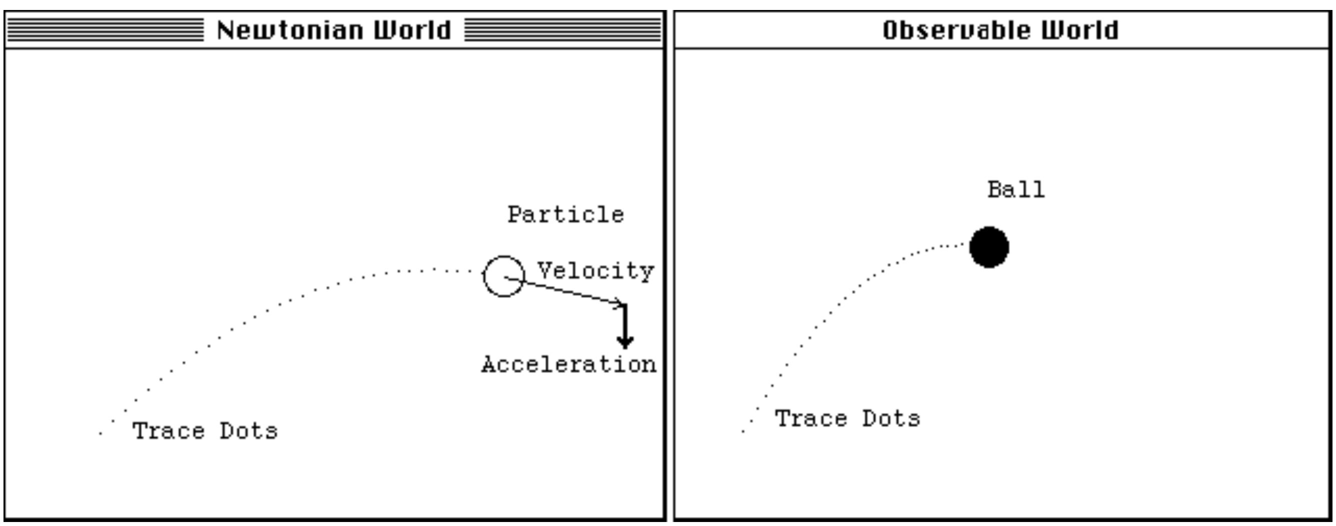

Figure 1: The Envisioning Machine (labels added)

When the simulation is run, the computer displays an animation of both the particle and of the ball moving across the screen. During the computer simulation, both the particle and the ball leave a series of trace dots behind them as they move, placing the dots at a uniform rate. These dots therefore contain information about the objects' speed, as well as its path. All the motions displayed by the EM are at constant velocity or constant acceleration.

2.1 Inspiration for the EM Design

The inspiration for the original design of the EM grew from research on physicists' use of mental models. By "mental model," I mean the capability to predict the behavior of a complex system by mentally simulating changes in the state of the system over time according to the logic of the system's component processes (Johnson-Laird, 1983; Gentner & Stevens, 1983; Jih & Reeves, 1992).

In one study of mental models (Roschelle & Greeno 1987), we presented experts in physics with diagrams of physical situations and asked simply, "What's happening?" The resulting think-aloud protocol revealed that experts reasoned about physical situations by creating two parallel mental models, one which represented objects corresponding to physical reality and the other which represented objects corresponding to abstract scientific principles. Physicists developed their analyses of physical situations by comparing the predictions of both mental models.

The initial goal of the EM project was to implement a graphic, direct manipulation computer simulation that externalized physicists' dual mental models. The EM "Observable World" window was intended to correspond to an expert's mental model of a physical situation; the EM "Newtonian World" was intended to correspond to an expert's mental model of abstract scientific principles.

The EM presents visual images that neither students nor physicists have ever seen before. The representation of velocity and acceleration vectors as arrows is common practice. The EM extends previous displays of this representation by presenting the arrows as animate objects that register their values in time -- as the particle moves across the screen, the velocity and acceleration vectors show the instantaneous velocity and acceleration. This real-time display represents the values of position, velocity, and acceleration changing over time, corresponding to their defined meaning. Previous static diagrams could not show changes over time. They could only represent such changes in space (for example, in a graph).

2.2 Design Rationale

The original EM design was guided by two principles: An overall metaphor of scientific visualization, and a specific emphasis on epistemic fidelity.

The scientific visualization metaphor guided many design choices. One example is the choice of representation. Velocity and acceleration can be represented in many forms:

o as lists of numbers (i.e. v = [10 20])

o as graphs of their value versus time

o as arrows.

The list of numbers was rejected because it is too limited to represent an expert mental model.

The EM does not use the graph representation for two reasons: First, although a graph is good for representing measurements of values, it is bad for direct manipulation -- students would have difficulty setting velocity and acceleration. Second, although graphs are good for representing a one-dimensional motion, it is difficult to visualize a two-dimensional motion from a graph.

Instead, the EM uses the vector representation, for three reasons:

o The vector representation is important in physicists' mental models.

o It is easy to implement direct manipulation.

o It can represent two-dimensional motions gracefully.

Even within this specification, further representational choices are necessary. One choice is whether to represent the concepts as "x" and "y" components, or as a single vector. EM uses a representation of velocity and acceleration as single vectors.

Another choice is among the forms of acceleration: constant acceleration, impulse acceleration, and uniform circular acceleration. While each reduces to the same set of definitions, the three forms of acceleration correspond to qualitatively different motions: They would require different direct manipulation interfaces.

Within the scientific visualization metaphor, a dominant rationale for the remaining EM design choices was epistemic fidelity. A good example of high fidelity design is the choice of scaling factors for the velocity and acceleration vectors. While the vectors could be scaled to arbitrary sizes (i.e. multiplied by a constant when converting from the arrow representation to real-time motion.), the length of the velocity arrow in the EM is scaled to correspond exactly to the change of position that would occur over one second of constant velocity motion. This scaling reifies the meaning of velocity as change of position because the tip of the velocity points to the place that velocity will be in one second.

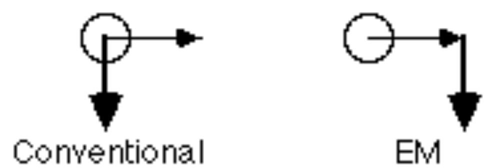

Figure 2: Differences in placement of the acceleration vector

A more controversial choice in the EM is the placement of the acceleration vector at the tip of the velocity vector. This placement emphasizes the causal relationship among position, velocity and acceleration: velocity changes position, and acceleration changes velocity. Thus, velocity is attached to the center position of the particle and acceleration is attached to the velocity. Under a high fidelity assumption, this representation should make the relationships among position, velocity, and acceleration more obvious. A more conventional representation, however, attaches acceleration to the center position of the particle.

3.0 Lessons About Epistemic Fidelity

Everyone agrees that people learn from experience. It is considerably less common to question what experience looks like from a students' point of view. Typically, educators and researchers assume that by describing the objects and relations that a knowledgeable observer would see in physical materials, they have described the experience that students have.

In my research, 10 pairs of high school students were video taped as they used the EM collaboratively for several hours. The students had no prior knowledge of physics. Their goal was to discover how to set the velocity and acceleration vectors in the Newtonian World window in order to match motions in the Observable World. In each of two sessions, the students were given 10 Observable World motions to match. At the end of each session they were interviewed. Following both sessions, students were given a multiple choice test that checks for a correct understanding of velocity and acceleration, and probes for common misconceptions.

Through the interviews and a detailed analysis of the students' video taped problem solving performance and talk, I identified three categories of knowledge that students developed. Based on these categories, I constructed a description of how students experience the EM. In order to calibrate this description, I encoded parts of it into a computational problem solving model, and demonstrated that the computational model produces similar behaviors to the behaviors of students. I also triangulated the descriptions against written tests and interviews, showing that distinctions in the descriptions correlate with differential performances on the tests and with students' explanations in interviews. This methodology and a comprehensive overview of results are described in detail elsewhere (Roschelle, 1991). Detailed case studies from this research appear in several publications (e.g. Roschelle & Clancey, 1992; Roschelle, 1992b; Teasley & Roschelle, 1993). In this paper, I draw examples from these studies that exemplify the rationale for shifting from an epistemic fidelity to a mediated collaborative inquiry point of view. I present these as a series of lessons learned.

LESSON ONE: Embodying a mental model in a physical object always introduces unwanted features. Internal contradictions of high fidelity design are ordinarily resolved by adopting arbitrary conventions, creating the problem for the newcomer of separating conventional from referential display features.

Some physicists who saw EM argued that it had low epistemic fidelity because acceleration appears at the tip of velocity rather than at the base of the particle. They suggested that this encourages the interpretation that acceleration acts at a distance, not on the object. This is a case of conflicting interpretations of the high fidelity principle: the EM representation is high fidelity in terms of the relationships among position, velocity and acceleration, but not in terms of the locality of action. In truth, the position of the acceleration is arbitrary and meaningless; only its displacement matters.

Empirically, I found no evidence in my research that students saw acceleration acting at a distance (Roschelle, 1991). Moreover, informal experiments demonstrated that the conventional representation, which draws both velocity and acceleration from the center of the particle, can be quite problematic. Students see it as indicating that acceleration and velocity are equal- and-opposite when coming to a stop (this is a misconception). Moreover, students often try to interpret a line connecting the two arrow tips as the result, rather than first shifting the position of the acceleration. Learners can construct problematic interpretations for any external representation.

Furthermore, in this case a contradiction occurs because there is no physical way to represent a displacement vector without putting it somewhere. There is always the potential for someone to interpret the placement as meaningful. Such arbitrary decisions plague the designer of physical representations for mathematical and conceptual objects, because these are often dimensionless or infinite (thus either invisible or impossible to fit into finite space).

LESSON TWO: Newcomers often did not use the EM appropriately, did not recognize the critical aspects of the display, or did not focus their attention the way a physicist would. The very features of the display that correspond to an expert mental model were often invisible to students.

For example, most students did not pay attention to the change in the velocity vector over time. Instead, they watched the circle that represents the particle. On many occasions, the experimenter told the students that it would be helpful in understanding the display to look at the moving vector. This advice was ignored: Students did not look at the changing velocity until they developed an idea spontaneously that made it worthwhile to look.

Conversely, students were fascinated by artifacts of the display. For instance, when the particle goes slowly the trace dots smudge together to form a line segment. Students wanted to identify the precise difference between distinct dots and a line-smudge. From the expert point of view, this is an unwanted artifact of the limited pixel density of the computer display. Experts readily ignore the smudges.

When students did notice relevant features, their choice of labels was sometimes problematic (Roschelle, 1991). For example, Jack and Ken understood the first few trace dots as measuring an objects' acceleration. These dots are in fact a better measure of initial speed. Carol and Dana got hung up by looking at distance and calling it speed. More generally, students labelled speeds with positive amounts only. This led to difficulties in their explanations. Whereas a scientist using all the real numbers (positive and negative) can describe gravitational acceleration as uniformly decreasing velocity, students using only positive numbers had to account for a sudden switch from decreasing to increasing speed.

Also, unlike scientists, students often did not know what to do in order to learn from this display. For example, students would often make EM motions that were as fast as possible; science educators made relatively slow motions. Of course, it was quite difficult for the newcomers to make good observations of very fast motions. Likewise, students often chose inappropriate settings of velocity and acceleration. For example, they would make initial velocity very small relative to acceleration. In this situation, the effect of initial velocity is negligible, leading newcomers to the incorrect hypothesis that initial velocity doesn't matter.

Finally, even when students labelled features appropriately, they often selected the wrong combinations of features for the highest levels of attention. Carol and Dana, for example, focussed on SETTING initial velocity but on OBSERVING average speed. In the parabola, they got confused by focussing on its height, width, and the total trip time, rather than focussing on initial velocity and change in velocity. Quera and Randi went astray by focussing on the position of acceleration, not on its direction and length. In particular, they described the acceleration vector as being attracted to a certain place, and dragging the velocity and the particle along with it. Only when the acceleration reached its place of attraction did the length and direction of acceleration have import, in Quera's account.

LESSON THREE: Despite a high fidelity representation, students construct mental models in a form that seems useful and natural from THEIR worldview. Thus, their constructed knowledge can be different IN KIND from the target knowledge, while still enabling the students to succeed at the given task.

A third class of failures has to do with students' sense of mechanism, observed in the form of a bias toward certain forms of knowledge and explanation. Students often are predisposed to first-order mechanisms -- mechanisms in which each controllable parameter directly relates to an outcome variable. In contrast, acceleration is a second-order concept; effects of acceleration on motion are seen through an intermediate variable, velocity. Nonetheless, students constructed mental models of the EM display in which acceleration was first-order. A common model was to map the velocity vector onto the initial motion, and speed and acceleration onto the later direction and speed (Roschelle, 1991).

Through video tape analysis, I identified three forms of knowledge that students constructed in order to solve EM problems and to explain their work. One might expect that because the EM is based on the definition of acceleration, students who succeed on the task would formulate something close to the definition of acceleration: acceleration is change in velocity over time. This was not the case. Students only rarely generated compact definitions, and then only at the very end of their experience with the EM. More commonly, they constructed knowledge using elements of three forms: registrations (features noticed and attended to), qualitative cases, and metaphoric abstractions (Roschelle, 1991).

A qualitative case is a group of qualitative regularities that apply within a particular kind of motion. Within each case, students constructed knowledge of many regularities. For example, within the case of a vertical ball toss:

HEIGHT IS PROPORTIONAL TO THE LENGTH OF VELOCITY

Qualitative case knowledge has the character of a loose aggregate, without any necessary internal consistency or coherence. To generate coherence, students bring metaphoric abstractions to bear. For example, students commonly explain the relationship between acceleration and velocity as a "pull." The acceleration pulls the tip of velocity, changing its length and direction. Such metaphors can unite the elements of a case, and can span across cases, as described in the scientific philosophy of Max Black (Black, 1979; Black, 1962).

Roschelle (1991) presents much detailed evidence about the nature of the qualitative cases and metaphor abstractions constructed by students as they use the EM. Herein, I will simply state an important generalization: Students' knowledge is different IN KIND from the knowledge attributed to the expert mental model. In particular, student knowledge is composed of relations among many fragmentary qualitative cases and metaphoric abstractions, whereas physicists link every element of their mental model to a single abstract mathematical definition.

Furthermore, the specific pieces of knowledge that students construct are often problematic from the scientific point of view. For example, students often construct a regularity that links the "width" of a parabola to the angle between velocity and acceleration. Scientists don't think in terms of widths of parabolas and angles between vectors. Students often choose knowledge elements that express relationships between the initial configuration and the global form of a trajectory (e.g. bigger velocity in a toss makes total trip time longer). Scientists prefer local relationships (e.g. bigger velocity means more distance per each unit of time), from which they derive global regularities. Finally, students have little interest in compact, consistent forms of knowledge; they often seem perfectly happy to construct many little pieces of knowledge which they adapt as they go along to solve particular challenges.

It seems quite unlikely that these problems could be overcome by strong epistemic fidelity -- a better picture of the expert mental model is unlikely to encourage students to construct mathematical definitions instead of qualitative cases and abstract metaphors. Moreover, a better picture is unlikely to change students' preferences for global instead of local regularities, and for fragmentary, adaptable knowledge over compact and consistent knowledge.

More precisely, many of the "constraints" in the expert mental model reside not in knowledge, but in the culture of representational practice to which the expert belongs. Students construct a model based on their experience and the constraints of their own community. Because a designer cannot reduce practice to theory (Clancey, 1992), we cannot fully embody a culture- specific reasoning practice in an artifact.

LESSON FOUR: Major transformations in a mental model occur when students encounter a problematic experience. Problematic experiences are hard to predict based on a description of an experts' mental model, though they do occur with regularity under conditions that can be described if one understands how students think.

The empirical data show an overall pattern in students' learning with the EM. As the students encounter the EM initially, they engage with it in a form of routine coping. The knowledge they construct in this first phase bears little similarity to scientific knowledge, though it is sufficient for solving most tasks. At some point along the way, usually after about one hour, students' experience becomes problematic: They become frustrated and confused, the device no longer presents a clear course of action, their loose assemblage of pieces of knowledge oscillates wildly between incompatible points of view, and they experience a genuine breakdown in their capability to cope with the EM. In their attempts to resolve these problematic experiences, students can transform their mental models dramatically, bringing them considerably closer to an expert model.

Surprisingly, some of the most problematic aspects for students are the least problematic elements from the point of view of an expert mental model. An example involves students' description of stopped motions. From the expert point of view, this is trivial: Velocity is zero. Students, on the other hand, (1) fail to distinguish between an instantaneous and an extended stop, and (2) expect forces at stop to "balance" (i.e. be equal and opposite). As a result, they are intensely frustrated and puzzled when the EM depicts a constant acceleration even when velocity is zero at the top of the vertical ball toss. From their first-order perspective, the presence of a "force" requires the presence of motion. As it turns out, a correct understanding of how to describe "stopped" motion is the last aspect of the EM that students come to conceive of in scientific terms.

The second circumstance that generates a problematic experience for students is the parabola. They expect velocity to be aligned with the beginning of the motion, and acceleration to be symmetrically aligned with the end of the motion. That is, students expect a parabola to be the result of conjoining two first-order parameters, one for the beginning of the motion and one for the end. When this fails to work, they make acceleration longer and longer, in order to make its effect in ending the motion more prominent. This makes the shape of the parabola less and less symmetric, so they then make it smaller and smaller. After a while, they get intensely frustrated because no settings of acceleration seem to produce a symmetrical parabola. As they get frustrated, they experiment with more varied settings of acceleration. Sooner or later, they set acceleration to point straight down. To their great surprise, this produces a symmetrical parabola.

But this makes no sense to students; they expect that a downward acceleration should produce a motion, with its latter half travelling straight down. This conflict becomes the occasion for a process of inquiry which seeks to transform their mental model -- to make it more coherent and unified. The result of this inquiry can be a mental model in which acceleration is a second- order parameter (a result documented in several case studies).

Thus, a detailed understanding of an expert's mental model will not tell us when and how students learn: One would not expect the "stopping" to be prominent, or articulated in detail, in an expert mental model. Nor would it be obvious that parabolic motion produces a conflict within students' first-order worldview. Epistemic fidelity therefore cannot focus the designers' attention on the aspects of the display that will most likely trigger and support learning.

These lessons attack the basic assumptions of the epistemic fidelity design perspective. Recall the definition of epistemic fidelity in terms of a correspondence between a physical representation and an abstract, ideal mental model. Under an internalization theory of learning, this correspondence should enable students to see and internalize the mental model. To the contrary, however, video tape analysis of students' learning showed that the correspondence was only visible to people who already understood the subject matter. Students often did not distinguish arbitrary from meaningful design elements, did not recognize the critical aspects of the display, and did not choose to make sense of the display in the way a physicist would. Furthermore, the conditions under which students learn cannot be predicted purely from an analysis of the expert's model. In summary, high fidelity design is not a guarantee of better learning outcomes.

4.0 Lessons About Mediating Collaborative Inquiry

Despite the problems outlined above, the empirical evidence shows that the EM can help students learn. EM is one variant in a long sequence of Newtonian computer simulations including Dynaturtle (diSessa, 1982) and ThinkerTools (White, 1993). Extensive studies show that these computer microworlds are among the most powerful techniques for helping students learn (e.g., White, 1993). My own video studies show that students who use the EM often change their concepts dramatically in ways that make their descriptions of motion much more compatible with Newtonian theory (Roschelle, 1991).

Thus, in this paper a crucial distinction is made between the propositions that (1) computer visualization tools can help students learn and (2) students learn because computer visualization tools are designed according the principle of Epistemic Fidelity. In the previous section, I showed that students do not learn because the visual model embodies an expert mental model; these correspondences are rendered invisible from within a students' worldview. My concern in this section is to articulate (1) positive principles that describe the nature of that learning, and (2) how tools can be designed to enable more students to be successful.

Barbara White's work is an exemplary example. White (1993) has performed extensive experiments with a similar tool called "ThinkerTools." White has shown that 6th grade students can attain conceptual understanding of velocity and acceleration that surpasses 12th grade students' understanding, by using ThinkerTools.

Three differences distinguish White's work from an Epistemic Fidelity design approach.

First, White developed ThinkerTools to support students' process of inquiry as they encounter the problem of describing frictionless motion. No pretentions are made that ThinkerTools corresponds to representations in an expert's mental model. Indeed, White has not studied physicists' mental imagery; images that appear on the ThinkerTools screen are not plausibly images in an experts' mental model. White's design supports the ways in which students' actually build knowledge, rather than assuming a process of internalization via an explicit expert model. The fidelity incorporated in ThinkerTools is computational, not representational -- ThinkerTools computes motion the way a physicist would, though it doesn't necessarily portray it with expert mental representations.

Second, White embeds students' use of ThinkerTools within a curriculum that explicitly teaches about the nature of scientific law and the process of scientific inquiry. Thus, White is explicitly giving students' specific ideas and processes to think with -- not just "embodied models."

Third, White assigns a strong priority to discussion among students, and between the teacher and students. By structuring these conversations in the image of scientific discussions, White creates a social climate (context) which further constrains the process of constructing and verifying knowledge.

Research with the Envisioning Machine has focused on understanding the process by which students construct knowledge and the relation of that process to design. I give a capsule summary of students' learning process here, and then discuss four design principles within a mediated collaborative inquiry process. The empirical details supporting this description of the learning process are found in Roschelle (1991).

Students who use the EM construct a mental model. At first, the mental models they form have little correlation with expert mental models. They register different features of the display than does an expert. They formulate different qualitative regularities than an expert would (e.g., the angle between velocity and acceleration is proportional to the width of the parabola), and they use metaphors (e.g., pulling, hinging, adding) where the expert mental model uses definitions.

Over time, however, students can transform their mental model into a closer approximation of scientists' mental model. The process by which this occurs is best described as "inquiry", in the sense meant by Dewey (1938, p. 104):

the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole.

Dewey's notion of inquiry flowed from his conception of a problematic experience (Dewey, 1938). He brought to attention the fact that we often experience life as routine coping with familiar situations. Some situations, however, are problematic. By this, Dewey means that the situation is confusing, unsettled, disturbing, and most importantly, lacking clear possibilities for action.

By "inquiry", Dewey means a practical activity that transforms the situation into one that is more clearly articulated, unified, and comprehensible -- and in which the directions for successful action are now clear. Importantly, this process involves uncovering previously unnoticed features of the situation and constructing new relationships that tie them together. Inquiry is a productive and constructive craft. Moreover, Dewey believed successful inquiries have objective results: Inquiry produces real changes in the coupling of the person and the situation with which he or she was engaged. This change is located neither in the person nor in the situation, but in interaction between person and situation (both physical and social).

Dewey's definition of inquiry refers not just to problematic experience, but also (equally) to the tools and practices that enable gradual transformation into a resolved, determinate situation. Clearly, an educative experience can only be successful if it both engages students in a problematic situation and provides suitable tools for the transformation of that situation. In the remainder of this section, I discuss design principles (in the form of further lessons) that describe the nature of such tools.

Before doing so, one thing must be made clear: The situations in which students successfully engage in inquiry are BOTH social and cognitive. Students who successfully learn with the EM or ThinkerTools (White, 1993) do so both because of their relationship to physical tools and because of their relationship to other students and teachers. Inquiry, in Dewey's sense (and in the sense it is used here), is a communicative, collaborative practice.

Much has been written about the benefits of collaborative learning, and of the set of trade-offs involved in assigning students to teams (e.g., Johnson & Johnson, 1987; Slavin, 1990). Collaboration appears to enhance learning by providing a context in which students are more likely to construct, elaborate and critique explanations (Hooper, 1992). The empirical case studies that substantiate this point with respect to the EM can be found particularly in Roschelle (1992), Roschelle & Clancey (1992), and Teasley & Roschelle (1993).

Collaboratively constructing shared explanations is not always easy, and is often troublesome. The lessons that follow highlight some of the problems that commonly arise in collaborative inquiry and present design guidelines that enable students to overcome these problems. Rather than orienting the designer to better ways of representing knowledge (as in Epistemic Fidelity), these principles focus on supporting communicative practices that enable students to collaborately construct, elaborate and critique explanations.

LESSON FIVE: Design displays that will extend students' engagement with problematic situations, and provide repeated access to the same problems. This will enable students to come to see different things each time a problem is accessed, and give them time to talk about a problematic experience before it disappears.

One function of technology in inquiry is to provide stable, long- term access to a problematic situation that may occur infrequently or may be short-lived. In the EM situation, motions occur in real-time. Thus, the aspects of a motion that are problematic to students may occur fleetingly. This impedes collaboration, because students find it hard to share an explanation when they cannot share sustained access to the puzzling phenomena.

As a consequence, one subtle but highly effective adjustment was made in the EM. In previous designs, the RESET command both moved the particle back to its initial position and erased the dots produced by the previous motion. The problem with this method was that students had to reset in order to make adjustments to vectors, but having reset they could no longer refer to the previous motion (in order to justify their adjustments). Thus, a student could not explain a change to his or her partner. In the final version of the EM, the dots are erased at the onset of the PLAY command; the dots are left on the screen to support conversations about the previous motion while adjustments to the vectors for the next motion are being made.

Likewise, because speed is a focal concept in students' inquiries, the EM provides a way to extend students' engagement with the experience of speed. Speed is redundantly represented in the trace dots, the length of the velocity vector, and the simulated speed of the particle across the screen. This selective use of redundancy pairs the ephemeral, but easily- interpreted representation of speed as simulated motion with the more persistent representation of speed as trace dot spacing. Interestingly, as the students become experts with the EM, they tend to watch the trace dots as the primary representation, viewing the running simulation as redundant, occasionally useful information.

It is not clear that expert mental models would have these features. When do the dots get erased in the expert's head? Who knows if experts even sees dots in their mental model? How many redundant representations of speed appear in the experts' mental model? These questions may not be answerable. On the other hand, it is obvious from the video tape evidence that students' process of collaborative inquiry requires the persistence of the dots on the screen, the ability to repeat a segment of motion, and the redundancy of representations. These features enable students to collaborate by allowing them to share sustained access to particular problematic situations over a long period of time.

LESSON SIX: Support selective attention to parts, and attention to the connections between parts and wholes. Provide tools for participants to establish a shared focus of attention and to trace connections from their local focus of attention to the overall context.

Another impediment to collaboration is that individual students often focus on different elements of a phenomena, or explain things relative to different contexts. Thus, another function of technology in collaborative inquiry is to provide a way of focusing attention on specific attributes, while nonetheless retaining the connection of those attributes to the broader context of the problematic situation.

For example, Roschelle & Clancey (1992) examine a case where two students collaboratively build an understanding of acceleration. This occurs through a process whereby students coordinate individual insights to construct shared meanings. At one point in the collaboration, Gerry generates an insight about how parabolic motion is produced. Hal asks for and receives an explanation, but indicates that he cannot make sense of it. As the case unfolds, it turns out that Hal cannot understand Gerry's explanation because he is not attending to the features of the EM display that support the explanation.

Eventually, Hal and Gerry are able to build a shared understanding. Many features of the EM enable these students to overcome the lack of a shared focus of attention that is blocking their ability to communicate. Herein, I shall mention just two such features.

First, whereas early versions of the EM play a continuous motion, later versions allow students to step through a motion one second at a time. Gerry explicitly chooses to use this feature to focus

Hal's attention. He runs the simulation forward one second, and then describes the difference he is attending to -- a change in the velocity arrow. Hal begins to focus on this object. The step by step motion slows the simulation to make it easier for students to synchronize their conversation with the simulation, and thereby communicate about the objects they are registering.

Second, the EM portrays vectors that are approximately the same length as a human finger. Gerry uses this affordance to communicate what he is seeing to Hal: he overlays his finger on top of the vector and imitates its behavior. This helps Hal pick this feature out of the visual field as a discrete object.

Similarly, students often use the trace dots as a way to make distinctions between instantaneous and average speed. At first, this distinction is very hard for students to make and to use. By pointing either at a local segment of trace dots or at dots representing the distance travelled in a set time, however, students can achieve a focus either on local speed or on overall speed. Importantly, these distinctions are made via communicative practices. In order to explain their ideas to someone else, students point to aspects of the screen that can provide a set of features visible to all parties.

In a truly mental model, focus of attention should not be a problem. Experts would only include in their mental model those features which are important to them. Thus, the principle of epistemic fidelity is of little help in deciding how to help learners focus their attention -- especially when they may not even notice those features that experts consider essential. The lesson of focus and context directs a designer's attention to creating displays that enable collaborators to achieve a common focus of attention and to connect their local conversation to a larger context.

LESSON SEVEN: Enable communicative action. Support communication through actions, and match visualizations to the language that students have available to describe the visualization.

Expert physicists have a language ready-at-hand in which to describe their mental models. Students do not. For example, students' language does not contain suitable distinctions between average and instantaneous speed. Nor do students readily use mathematic constructs (e.g., "a derivative") as a basis for formulating their ideas. In addition, many students have trouble expressing their conception through language at all. They fall back on gesture as an alternative mode of communication (Crowder & Newman, 1993). Thus, the ability to talk about a mental model depends upon the community of practice to which a person belongs.

This point applies to many of the design decisions that make the EM a success. For example, many students communicate "an idea" to another student by making an adjustment to the vectors. Early on it became apparent that students were having trouble tracking the changes made by their partners.

Two specific changes to the design were made. First, the vectors were constrained to a grid. As they were adjusted to each new grid setting, an audible click occurred. Second, as a vector was dragged, the previous vector was left visible on the screen (so that students could easily observe the difference between the previous and current settings). These changes enabled participants to interpret the communicative intent of their partner's actions more clearly. Specifically, while using the EM students often negotiate qualitative cases through action: One student might say "its too fast", while the other student makes the velocity arrow shorter (Teasley & Roschelle, 1993). This communicates a qualitative regularity between length of velocity and speed.

Similarly, the EM was explicitly designed to enable students to use the metaphor of "pulling" to describe the relationship between velocity and acceleration. The metaphor of pulling can enable students to make sense of acceleration as a property that changes the length and direction of velocity simultaneously -- they see the acceleration vector pulling the tip of the velocity vector to a new location in velocity space. When students lack the concept of a derivative, they can use pulling as a qualitative approximation of the idea. And although pulling is not the same concept as a derivative, through combination with other metaphors and gradual refinement, students can generate an abstract concept that is quite similar to the derivative concept. Thus, while placement of the acceleration arrow in the EM is unconventional and does not correspond to an expert's mental model, this placement does make it easier for students to communicate about a critical concept.

LESSON EIGHT: One should design activities which actively engage students in doing and encounter meaningful experiential feedback as a consequence of their actions

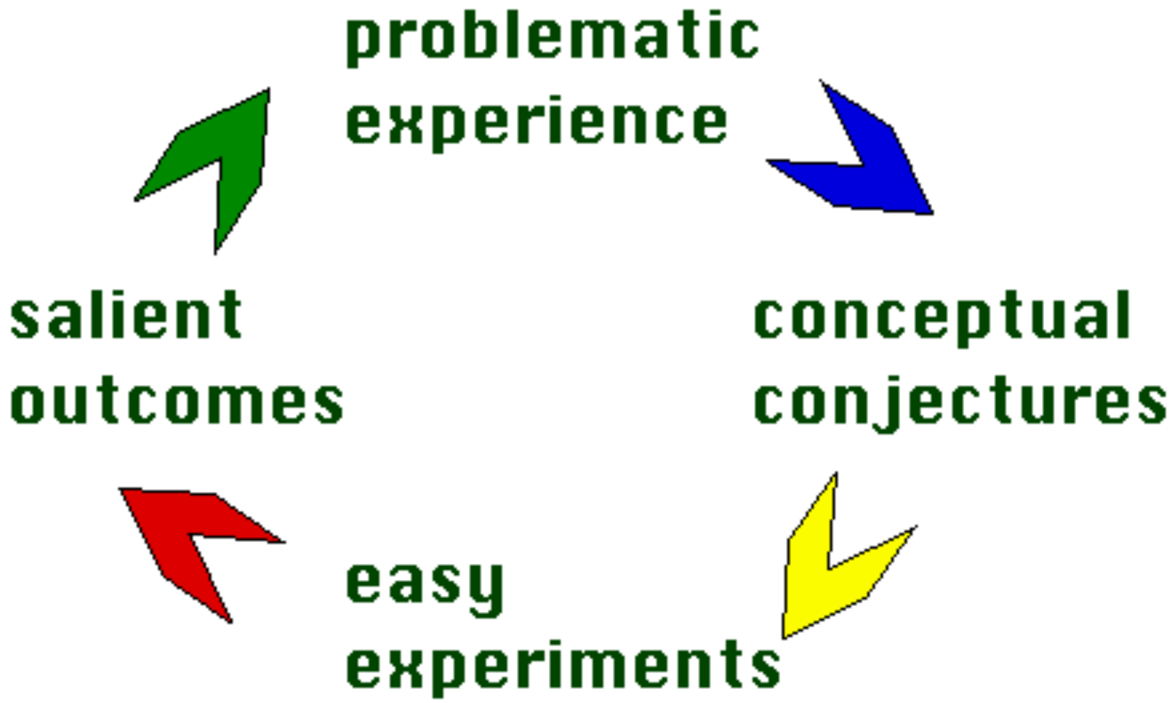

Figure 3: Dewey's Cycle of Inquiry

A defining feature of interactive learning environments is that they offer students an opportunity for learning by doing. Learning by doing, however, means many things to many people. The EM design closely follows a further specification of learning by doing: Dewey's account of inquiry. Inquiry is a cycle of four stages, as depicted in Figure 3.

Lesson 5 already discussed how the EM is designed to ensure that students encounter situation that are problematic from their point of view. Although it is important that students fully experience a problem as their own, it would be a mistake to dwell too long in this problematic state. Hence it is important that this stage quickly gives rise to conceptual conjectures.

The design of the EM uses objects which are highly suggestive of conceptual meanings. For example, arrows readily evoke direction and force, as well as related concepts like pulling and guiding. Moreover, students can easily make things bigger or smaller, and align directions. Thus when then encounter a problem, students quickly generate conceptual conjecture.

The conceptual conjecture phase must give way to easy experimentation. As students' problems are encountered as experiences, they must be resolved in experiences. Therefore it is important that the EM uses direct manipulation techniques to enable students to quickly carry out experiments according to their conjectures. This is easy as adjust a vector with the mouse, and running the simulation. Ease of experimentation encourages students to subject their concepts to the test of experience.

Experimentation, however, would not be useful if outcomes were obscure. Herein lies a subtle but crucial feature of the EM design: it gives students a very simple, perceptual criterion to determine success. Motions must be "the same." Interestingly students operationalization of "the same" evolves as they use the simulation. Many students begin by simply making motions that go in the same direction. Once this is achieved, their eyes tell them that speeds need to be the same too. In adjusting speeds, they find that they cannot make motions "the same" unless address change in speed as well. Finally, as students progress, they start to change from a simple perceptual judgement of "the same" to a more instrumental judgement that makes measurements using features such as the trace dots. Importantly, students can make all these judgements without external authority. The EM gives students a criterion for success that they can readily interpret and use.

5.0 Conclusion

Suchman (1987, p. 69), in her analysis of planning and situated action, articulates a point that resonates with observations of students' learning while using the EM:

For students of purposeful action, however, the observation that action interpretation is inherently uncertain does have a methodological consequence: Namely, it recommends that we turn our attention from explaining away uncertainty in the interpretation of action to identifying the resources by which the inevitable uncertainty is managed.

As was apparent in research on students' use of the EM, "inevitable uncertainty" applies not only to interpretation of actions, but also to interpretation of displays. Designers of high fidelity displays try to eliminate this uncertainty by perfecting the denotational relationship between a display and the ideal form of the underlying concepts. Unfortunately, gaps in worldviews usually prevent learners from decoding the denotational relationship and acquiring the target understanding. Hence, rather than merely representing mental models accurately, designers must focus on supporting communicative practices that enable ambiguities and uncertainties to be smoothly resolved. Designers must provide a medium that facilitates collaborative inquiry.

Displays with high epistemic fidelity are not necessarily the best for negotiating the meaning of a conversation (Roschelle & Clancey, 1992) or for demonstrating a concept (diSessa, 1986). A simple example is the fact that the EM simulation is stopped while the student adjusts velocity and acceleration. Strictly speaking, this does not make sense: If an object has a non-zero velocity, it is moving. Time cannot be "frozen." Conversely, properties that violate high fidelity often make for good conversations. For example, discrete numerical simulations often introduce an accumulating error as the simulation progresses. Noticing this error can stimulate a conversation about the difference between a theory and a numerical simulation. The Alternate Reality Kit (Smith, 1986) takes this approach to the extreme, purposely displaying interactive worlds that violate scientific laws in order to stimulate an understanding of the laws of our world. Thus, the lack of high fidelity can create the background for a discussion of serious scientific issues.

Another concern is the presence of internal conflicts in the application of Epistemic Fidelity. In the EM, such internal conflicts occurred when ideal mathematical objects such as the acceleration displacement vector were given concrete representations and thus came to embody unintentional, low- fidelity properties. Similar conflicts occurred when continuous motion was (necessarily) modelled by numerical simulation in finite time steps, with finite size points. Concrete or reified representations, which are often thought to be the best for learning, are especially prone to introducing unwanted properties, and thus reducing epistemic fidelity. These concerns with Epistemic Fidelity are supported by the data from video analysis of the EM. It was observed that students do not interpret displays as intended despite the high fidelity of the representation, from an expert's point of view.

Thus, it is important to make a distinction among ways of applying the mental model concept to computer system design. On one hand, it is essential that students have a good mental model of how the computer system works (Norman, 1991). Thus, students control the EM using commands named PLAY, FORWARD, and BACKWARD. This tape recorder model makes it easy for students to run the simulation. On the other hand, educators who design software sometimes attempt to map a conceptual mental model to a set of computational objects. This is a generalization from (a) learning how to control a computer system to (b) learning how to control a computer system in order to understand the system of concepts it denotes (or represents). Such generalization does not work across the boundaries of worldviews: Problems of knowing what to do, where to look, and how to make sense diminish the possibility of the student seeing the intended epistemic correspondence.

To summarize, while it is generally true that designing a good mental model will help users control a computer system, representing knowledge in a computational model does not necessarily help students construct the intended knowledge. Designing a medium that supports communicative practices and constructive learning processes is at least as important as representing knowledge with fidelity.

Epistemic fidelity and mediated collaborative inquiry perspectives also suggest different design methodologies. Epistemic fidelity lends itself to top-down specification: Researchers can study an expert model and use it as a specification for the interface to be designed. Mediating collaborative inquiry suggests an iterative process incorporating such ideas as participatory design (Greenbaum & Kyng, 1991), collaborative rapid prototyping (Bodker & Gronbaek, 1991), and video interaction analysis (Suchman & Trigg, 1991). Describing these techniques fully is outside the scope of the this paper.

Iteration and rapid prototyping correctly suggest a strong trial and error component of the process. However, this method is not merely trial and error. Participatory design, collaborative prototyping, and video interaction analysis are powerful techniques for identifying communicative practices that enable collaborative learning. The lessons I have described suggest ways of selectively emphasizing experimentation so as to focus design energies on producing a medium that empowers conversational and learning processes, rather than merely increasing the fidelity of knowledge representations to mental models. While trial and error is part of any designer's repertoire, a design perspective strongly influences the outcome by determining what factors are considered or ignored. All too often, communicative practice and learning process have been ignored in favor of knowledge representation.

Are the epistemic fidelity and mediated collaborative inquiry perspectives incompatible? It is an essential feature of the EM (and other similar simulations) that they compute motions in accordance with a Newtonian worldview. Faithful computational fidelity to Newton is a prerequisite for success. Computational fidelity, however, is a considerably weaker constraint than epistemic fidelity: It specifies computational relationships between successive states in the simulation, but not interpretative or epistemic relationships between different forms of imagery. The empirical data do not bear out the view that students directly profit from the higher level of epistemic correspondence; experts see the correspondence, but learners from a different worldview do not.

In addition to computational fidelity, I have argued that learning technologies should be designed to support the social process of inquiry through which students learn. Mental models are constituted not just by theoretical knowledge, but also by a range of practices that cannot be encoded in observer-independent form. Thus, an external model cannot encode a target mental model into a "conduit" such that a student coming from another worldview can readily decode it.

External models, however, can support communicative practices, and conversations across worldviews are possible under the right circumstances. The necessary affordances for inquiry and collaboration include extended engagement with problematic experiences, establishment of selective attention to parts and wholes, support for communicative action, and an activity that makes sense within both worldviews. By supporting communicative practices that seek to overcome ambiguities and uncertainties in meaning, designers can enable conversations in which participants gradually learn to participate in the expert worldview.

Author Notes

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