2. Trends and Techniques in Computer-Based Educational Simulations: Applications to MBL Design

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Abstract. Computer-based educational simulations are seen as a subset of the larger set of instructional approaches whose goal is to help learners come to a better understanding of real, complex systems. In this paper, a conceptualization is developed for the domain "understanding complex systems" and within this, a scheme is offered whereby computer simulations are considered relative to interrelated cognitive and instructional aspects. Techniques and trends in simulations relative to visualization, interactivity, and intelligence are discussed within the framework of the scheme. The relationship between microcomputer-based laboratory environments and computer-based simulations in science education is considered, as well as the emergence of MMLs—multimedia laboratories. MBLs and MMLs are compared with respect to the trends of visualization, interactivity, and intelligence as a way of identifying common aspects with simulations in science education. Promising directions for improving the effectiveness of both MBLs and simulations are suggested.

2.1 Introduction: Computer-Based Simulations and MBLs in Science Education

This paper presents an analysis of certain concepts, strategies, and techniques for understanding complex systems. In particular we limit our focus to computer-related learning environments for science education. We first discuss simulation software, and then argue that this type of software overlaps in many ways the category related to Microcomputer-Based Laboratories (MBLs). We particularly focus on certain techniques and trends in the design of these learning environments, in particular, visualization, interactivity, and intelligence. We also introduce MMLs—Multimedia Laboratories—and consider these as well in terms of the three major trends discussed in terms of simulations and MBLs.

Computer-based simulations (for convenience, referred to only as simulations during the rest of this paper) have been defined and categorized in many ways, for example, sometimes related to the degree to which the variables within the system being simulated are well defined (Collis, 1988), to the degree of learner control of

events within the simulation (Gredler, 1986), or if the system being simulated is natural, man-made, or imaginary (Schaick Zillesen, 1990). Regardless of the perspective, a simulation can be very simply defined as computer software that takes as input some values of certain scientifically interesting variables, processes them in some way, and then presents them in processed form to the learner, who may or may not have the opportunity to further manipulate them. The goal of the experience is to better understand the complex system represented by the variables. In this broad view, microcomputer-based laboratories (MBLs)[1] are generically similar to simulations, although of course the origins and types of data and variables and the ways in which data are input into the computer differ. Although it is not the case that MBLs are a subset of simulations, there is enough functional and didactic overlap between the two categories of electronic learning environments that key observations relative to the instrumentation of simulations can also be useful to the design of instrumentation for MBLs. We will focus primarily on simulations in the first part of this analysis, but in the second part make the extension to MBLs.

2.2 Trends and Techniques

Our focus in this analysis is also on the instrumentation of simulations (and of the software component of MBLs). Instrumentation aspects include screen design, design of output display, instructional design variables in the software itself, choices available as design options in the software, and other issues controlling the designer of the software. In particular, we consider trends and techniques relative to visualization, interactivity, and intelligence as important aspects of instrumentation design.

2.2.1 Visualization

The rapid evolution of the technology related to the display and manipulation of visualization in computer environments is of course well known. The increasing use of interactive video in schools, the ability to store huge amounts of visual material on a single CD-ROM, the capacity to digitize photographs and even moving video so that it can be manipulated within software environments via video windows or by using DV-I technology to compress and decompress moving video so that it can be manipulated within a simulation environment have led to a corresponding increase in the quality and quantity of visualizations in educational software and particularly in simulation environments. We see the quality, the speed of appearance, the "look" of graphics in simulation software improving enormously even by the year. And we see a strong interest in interactive video as a component of science simulations. A comparison of computer simulation programs on the commercial market over the past ten years makes this line of development abundantly clear.

[1] Microcomputers interfaced with traditional laboratory apparatus to carry out functions of data collection, handling, and display. The term "MBL" was introduced by Tinker at TERC.

But we are not convinced that this visual explosion always (or even very much) is being driven by cognitive and instructional theory, or by instructional needs identified by a prior examination of the domain "understanding complex systems." We suspect a technology push motivates some aspects of interest in increased visualization. Thus one purpose of this paper is to map various aspects of visualization onto a cognitive-instructional framework for simulation but also more generally to contribute to the larger question of the relationship of visualization to learning given the emerging possibilities of multimedia (Moonen & Stanchev, 1992).

2.2.2 Interactivity

Aside from visualization, we are also very much aware of two other trends that are now of considerable interest not only with respect to computer simulations but to educational software in general and even more broadly, to many aspects of education. These are interactivity and what we might call metacognitive support, or "intelligence." Interactivity is easier to discuss. Vygotskyan theory, where learning is seen to occur as a result of social interaction, has contributed to a broader view of interactivity as part of computer-augmented learning experiences (Forman & McPhail, 1989). In addition, ideas about computer-supported cooperative learning are becoming increasingly influential in the design of learning activities involving educational software (see, for example, Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989). Interactivity has always been seen as an important feature of educational software, but this was generally understood to be learner-software interaction. Now we see stress on the importance of embedding learner-software interaction within human interaction in order to motivate and produce learning (Tennyson & Thurlow, 1987). But even within the learner-computer interaction framework, many new options are becoming available with simulation software, such as those related to model exploration (i.e., implementing a hypertext-like exploration of a model, allowing a change of view and zooming in/out of concept domains; see Hoog, Jong, & Vries, 1991, p. 376). Thus it is appropriate to also consider interactivity in our analysis of trends and techniques in simulation environments and to attempt to relate these interactivity options to a cognitive-instructional framework. In addition, science telecommunications networks, such as the National Geographic Society's Kids Network Program, bring interpersonal interactivity during the collection and analysis of scientific data far outside the boundaries of the classroom (Songer, 1989).

2.2.3 Intelligence

The trend we call "intelligence" is harder to define but it involves a deliberate focus on metacognition and the stimulation or support of metacognitive processes in the learner. Thus "cognitive tools" are becoming popular, and software making use of hypertext and hypermedia organization of learning materials are fueling this interest (Kommers, Jonassen, & Mayes, 1991). We see "idea processors," "semantic mapping," and other kinds of "mind tools" assumed to be valuable and appearing more

and more as embedded tools in educational software (Jonassen, 1988). The assumption is, among other things, that such tools stimulate metacognitive processes such as reflection and epistemological analysis, processes considered important for learners using computer simulations (Jong & Njoo, 1990).

We also see as another direction of this trend toward more "intelligence" in simulation software the increasing interest in including diagnostic or tailored (i.e., "intelligent") tutoring as functions to better steer or support the learner during interaction with the simulation (Hollan, Hutchins, & Weitzman, 1987; Towne, Munro, Pizzini, Surmon, Coller, & Wogulis, 1990). The extent to which this intelligence is electronically steered by the software or is available (either as part of the electronic environment or apart from it) as an optional resource for the teacher or student is also an emerging area of interest with respect to simulation environment design (Thomas & Hooper, 1991).

2.3 Purposes of the Analysis

As specialists in the design of instrumentation for new technologies we interact with colleagues who are engrossed in the implementation of these trends relative to visualization, interactivity, and intelligence in educational software and in particular in simulations. We see their, and their students', enthusiasms, and we hear similar enthusiasms at conferences and vendor exhibitions. However, we feel the need for a systematic way to consider these trends and techniques in an instructional/cognitive setting. We want to have a better sense of the critical problems students encounter in understanding complex systems with the help of simulations, and from this we want to identify the types of techniques of most help in dealing with those problems. Simply stated, we want to confront the urge to be fascinated by new developments in technique and technology. In a time of mushrooming new technical possibilities we want to reconsider the domains in which those possibilities can be applied so we can better identify the best fit and most promising cutting edge for their application in learning.

Thus the purposes of this discussion are:

- At the most concrete level, to suggest design guidelines based on instructional/cognitive principles for the implementation of various techniques related to visualization, interactivity, and intelligence in educational computer simulations and by extension, to MBL software design.
- At a more general level, to stimulate reflection on "critical attention areas" from a cognitive/instructional perspective in the design of computer-based instrumentation whose aim is to help students better understand complex systems.
- At the most general level, to suggest a new view of the domain, "understanding complex systems," in which computer simulations, MBLs, and also the emerging "multimedia laboratories" (MMLs) are educational tools.

2.4 Conceptualizing the Domain, "Understanding Complex Systems"

We begin by suggesting a framework for the development of students' capabilities to understand complex systems. First we clarify various aspects of this domain and the cognitive-instructional dimensions we will suggest to represent increasing capability within the domain. Following this, we relate the domain to simulation software (and later to MBL software) and use the framework to focus on the three trends of visualization, interaction, and intelligence.

2.4.1 Systems

A first step is to define "complex systems." There are many formal definitions, of course, varying in their components and terminology according to the discipline (and author) making the definition. We will define a system as a set of interrelated variables. For our purposes, a complex system is a system where the interrelationships between the variables influences the current state of the system, so one cannot say that the output or current state of the system can be fully understood by knowing the value of any one variable within it or even by knowing about the values of the variables in isolation. The relationship among them is part of the system.

Systems have component parts and also have state-transition relationships. Sometimes our interest with respect to "understanding" a system stops at knowing the component parts and their hierarchical or taxonometric relationship (example, the organizational chart of a company). Other times our interest focuses on the input-output aspect of a system. This can be addressed using a "black box" approach, where what goes in and what comes out matter, but how it gets transformed within the box is of little or no direct importance. Most often, we are interested in both aspects.

Sometimes systems are well defined. A machine, for example, has a finite set of components and well-defined relationships. The output of the system has a functional relationship to the current state of the components (although any system can malfunction or unexpected variables can influence its performance). In theory at least we can develop an algorithm to describe the output of the system based on knowledge of the values of a specified set of variables. Often this algorithm is expressed mathematically. In reality 100% certainty is not possible for any system; however, we will define a well-defined system as one where a functional relationship can explain the "usual" output of the system.

In contrast, there are many systems which are not well defined. These systems operate at best in a probabilistic manner; we can fashion an algorithm, but the probability that the algorithm can predict the output of the system given input on the variables called for by the algorithm is middle to low. This can be because we cannot in a practical sense specify all the variables that influence a system, those that we can identify we can only imperfectly measure, and we cannot state more than general tendencies in the relationship between the variables. Most complex systems fall in this category, particularly those involving human behaviour (i.e., politics, perfor-

mance of organizations) but also systems relating to the environment, and to settings such as agriculture, fisheries, or human/animal/plant physiology. With the latter type of systems the best we can do is deal probabilistically within them. We can, of course, "pretend" that a system is well defined, and that a certain set of variables and a certain algorithm will give a reasonable resultant state of the system, but our result must be understood to be an estimation if we are to understand the complex system as it "really" is.

2.4.2 Understanding

A second basic clarification with respect to the domain "understanding complex systems" relates to the word "understanding." We have already noted that "understanding" can mean to know the component parts of a system and their structural relationship, to know the most likely output of a system given a certain set of inputs, or a combination of these. Then there are intellectually different levels of understanding as well. These can range from having only a general overview of a system, through knowing key concepts and variables and how they are interrelated in the system, through being able to solve problems in the system, and also to being able to "stand above" the system and interrelate it with other systems or see how to change the system itself in order to change the likelihood of a certain output state. These levels relate to the learner's cognitive activity.

Another aspect of understanding relates to the actions and intentions of the teacher or instructional designer to help bring about understanding. These can be categorized in terms of instructional techniques—in particular, providing appropriate help, providing clarification, giving feedback, providing task guidance, providing appropriate tools, and providing a rich learning environment. They can also be categorized in terms of the overall intention of the teacher's instructional activity. Such intentions can include providing a motivating orientation, developing specific concepts, guiding the application of concepts to new settings, or stimulating reflection and analysis.

The meaning of "understanding complex systems" is thus related both to the cognitive characteristics of the learner as she is engaged in the act of "understanding" and the strategies for facilitating that understanding employed by the teacher or by the designer of learning materials. These two dimensions are interrelated, with "recalling"/"providing motivation" as likely to be associated with a minimally sophisticated level of system understanding, and "creating new perspectives/stimulating higher order thinking about the system" as a combination approaching rich understanding of the system. Figure 1 shows this relationship. Also illustrated in Figure 1 are four so-called critical transitions in the development of understanding of complex systems. These are illustrated by the numbered dots and the resultant-like vectors emerging from one dot and pointing to the next.

It is clear we have made simplifications here. The cognitive-activity axis, for example, should be seen as a continuum, where "noticing" precedes "recalling/connecting" with previous experience, which leads into an assimilation/accommodation loop (to use terminology of Piaget), leading to a gradually enlarged and/or strengthened knowledge base,

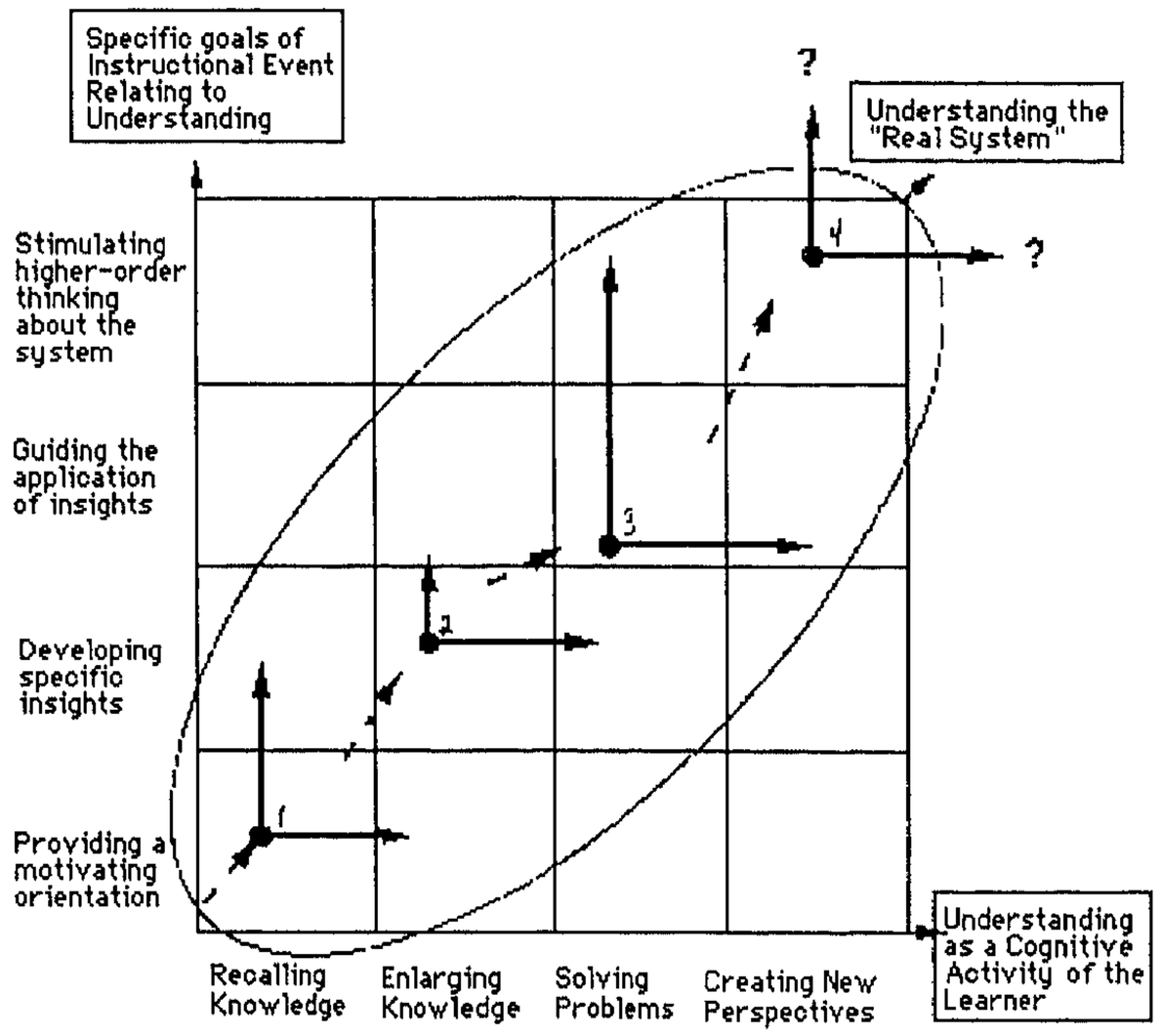

Figure 1 Critical transitions in increasingly sophisticated understanding of complex systems

which is then applied to solving problems of various degrees of complexity, which in turn can lead to synthesizing and creating new perspectives. However, this level of cognitive sophistication can also loop back to reflective strengthening of one's knowledge base, so that, also in turn, new things about the problem space can be noticed and the whole cognitive progression entered again from the origin.

The dimensions of the cognitive-instructional framework shown in Figure 1 are relatively familiar. What might be new is our conceptualization of four critical transitions relative to the framework that we believe are of particular importance to the design and employment of computer simulations. We are defining as critical transitions in the cognitive/instructional matrix those periods when a learner is not "ready" on his own to adequately perform a level of cognitive activity but needs or will particularly benefit from instructional support. The large dots on the grid symbolize points of learner "self-sufficiency" as she progressively comes to better understand a complex system, the vertical arrows leading from the dots represent the categories of instructional goals which seem most appropriate to lead/support the learner as he progresses from one to the next level of cognitive "self-sufficiency." The movement from the origin to the top northeast corner of our cognitive/instructional matrix represents the progression toward maturity with regard to understanding a complex system. We also include an elliptical area on Figure 1 to indicate an hypothesis of the boundaries of variation of instructional strategies most appropriate to different cognitive-activity levels. Clearly, relative to the learner and the definition of "under-

standing" in a given situation, the endpoint of the understanding process may stop at or between any of the dots within this elliptical path.

With these critical points identified relative to cognitive/instructional understanding axes, we are ready to consider visualization, interactivity, and intelligence as design aspects of computer simulations.

2.5 Visualization and the Critical Transitions

2.5.1 Representing Complex Systems through Visualizations

When we approach the task of "understanding complex systems," it is not often that we can directly deal with the one and only one exemplar of a system without any need for representation of the system. We must represent the system in some way, either by providing data that exemplify the system for direct examination (as with MBLs), or by providing a model to represent the system, as with simulations. Here we have another major issue in the domain of "understanding complex systems"—how well does a set of data or a representation reflect the "real" system? The fidelity of the representation of a system relative to the "real" system is a major issue in simulations (Hoog, Jong, and Vries, 1991, for example, discuss input, output, and time fidelity). Of course, the level of fidelity by definition must be weak in non-well-defined systems. Fidelity is both a quantitative and a qualitative concern, dependent on the level of understanding of the learner and focal point of understanding (structure or behavioural) that is important to given learners. Reigeluth and Schwartz (1989) for example, argue that "full" fidelity might be overwhelming for novice learners, and Towne and Munro (1989) argue that multiple levels of representation complexity should be available within a simulation, to be chosen according to the knowledge level of the learner. Thus while system representative could be expressed through abstract symbols such as formulas or through numeric variable values, it is likely that visualization will be important to both input and output fidelity.

2.5.2 Visualization Complexity

Visualization in simulation software can vary on several dimensions: for example, from symbolic to realistic, or from still to moving. Gradations of detail also occur as another dimension. A graph is an example of a symbolic visualization, often still, but it could be shown in motion, relative to changes in the values which it is symbolizing. In simulations, we can identify five major types of visualizations: still and moving graphs, sketches and drawings, digitized photographs, animations, and moving video. The category sketches and drawings is most ambiguous, in that sketches may include abstract iconic representations or minimalistic realistic representations and thus the boundary between sketches and drawings and other types of visualizations is one of gradation rather than demarcation. Currently, the use of windows for overlapping graphics in simulation is also of interest (Schaick Zillesen, 1990).

2.5.3 Relating Visualization to the Critical Transitions

Over the past decade we have noticed a definite trend with respect to visualization in simulations, especially those for science education. In the early 1980s, if simulations had visualization aspects, these were typically simple line drawings or graphs. Simple animation, such as a fish responding to another member of its pertinent food chain, also were popular. However, in the course of time, the quality of high-resolution graphics available on school computers consistently improved, as did the attempting-to-be-realistic visualizations found in simulation software. New trends are, of course, still occurring in hardware. CD-ROM storage allows the capture and display of large numbers of digitized visualizations. Interactive video systems are becoming more affordable and popular. "Multimedia," often involving an integration of graphic visualizations, animation, and even moving video (perhaps only yet in a window and of short duration and grainy quality, but nonetheless, moving video) now dominate software catalogues and educational software exhibitions. Thus it would seem that the trend relative to visualizations in simulations is simple to describe—toward more visualizations, better quality visualizations, and moving video.

In reference to our cognitive-instructional grid in Figure 1, it would seem that one of two assumptions about visualizations in simulations may be justified. One of these is that "more and moving" is better in terms of visualization, so that no matter where one is on the cognitive-understanding grid, making available quality video in digitized environments is generally a good thing. Another assumption may be that simple visualizations may be best for "simple" cognitive-instructional locations on the grid, but the more complex the cognitive and instructional task becomes, the more complex visualizations are desirable. Thus if we use a different meaning for an overlay sketch of an ellipse, where we interpret narrowness of the ellipse as simplicity (i.e., line drawing, simple graphic) of visualization and greater width of the ellipse as complexity of visualization (complex animations, moving video), the first assumption would involve an overlay such as a rectangular prism over the roughly diagonal path from no to mature understanding shown in Figure 1. In contrast, the second assumption would place a wedge-shaped figure over the diagonal path, narrow at the base, but continually widening as instructional-cognitive complexity increases.

We, however, do not endorse either of these approaches. Relative to the first critical transition area (the lower-left dot in Figure 1), we think rich and realistic moving video may well be best for providing a motivating overview and for triggering the maximal number of recollections for the learner. However, we think the tasks associated with the next two critical transition areas (the middle two dots in Figure 1) are more likely to benefit from simple, representational visualizations, where the learner's attention is guided as cleanly as possible to a focus on relevant aspects of a concept or problem situation. Rich and detailed visualization may in fact distract the student rather than help him focus at these stages of understanding. However, as the learner approaches Critical Transition 4, an overall look at the full system in its complexity, but with the ability to zoom in and out, to digitize the visualization of the system so

as to be able to experiment with the manipulation of its components in ways outside the model of the simulation designer may be highly effective techniques.

2.5.4 Visualization Guidelines: The Figure 8

Thus, as a generalization, we suggest that in software for understanding complex systems, interactive video may be particularly useful for orientation; graphs, minimalistic drawings, and simple animations may be best for enlarging knowledge and solving problems; but that advances in digitized video within the simulation environment may be best recommended for learners approaching the "Creating new perspectives/Stimulating higher-order thinking" Critical Transition. We visualize our hypotheses about visualization in Figure 2. The area repre-

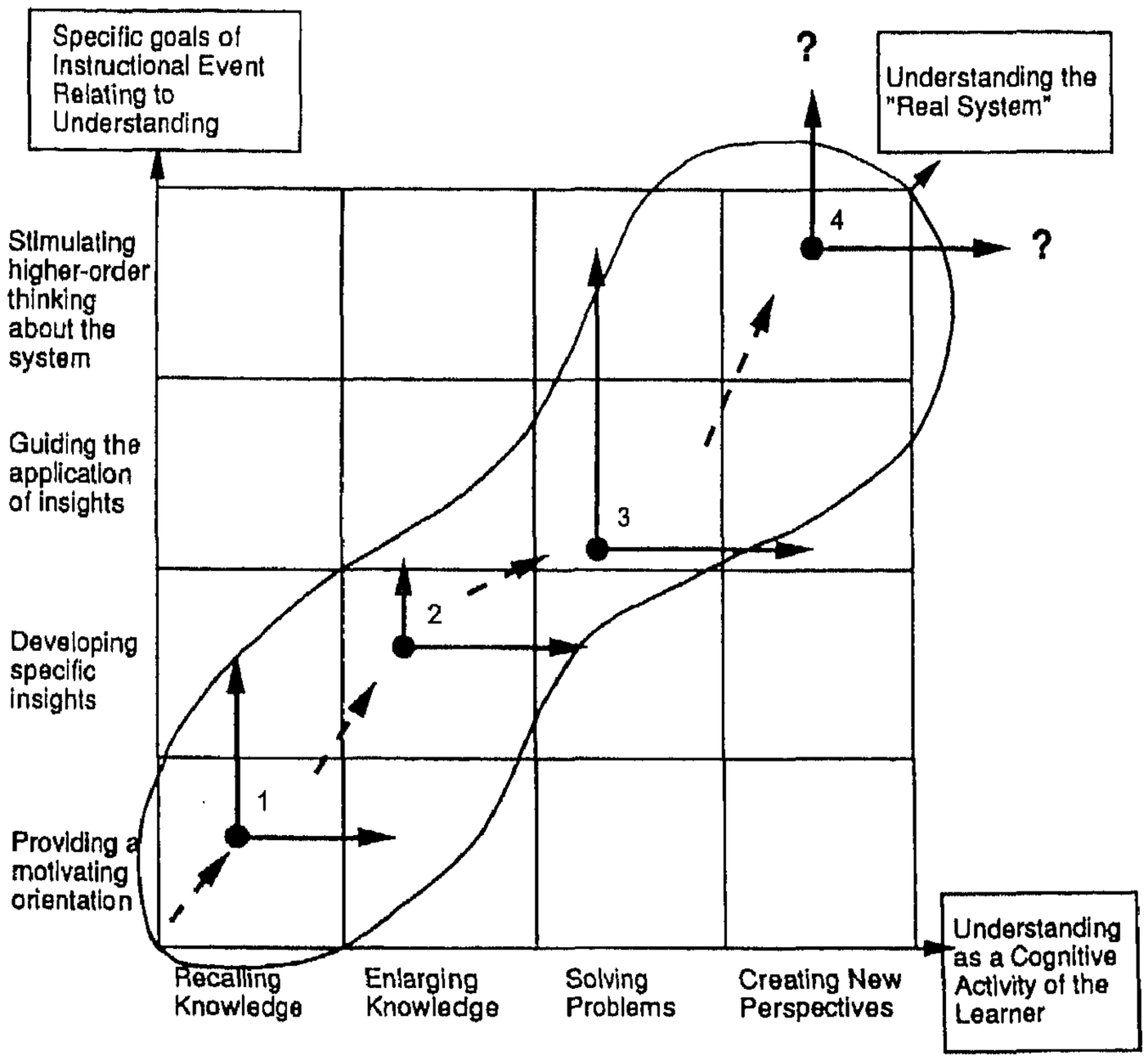

Figure 2 Projection of visualization trends in educational computer simulations. The wider the ellipse, the more appropriate a complex type of visualization such as moving video. The narrower the ellipse, the more appropriate a "simple" visualization such as a sketch or graph. Thus complex visualization is hypothesized as an appropriate design option in the areas of Critical Transitions 1 and 4, and simple visualizations in the areas of Critical Transitions 2 and 3.

senting our hypothesis about visualization guidelines has a resemblance to a figure 8, thus our choice of terminology.

2.6 Interactivity and the Critical Transitions

Earlier we noted trends in interactivity in educational simulations, in particular, trends toward more interpersonal interactivity as part of the simulation-use experience, and trends toward the provision of more options in the software for learner-choice of where and what he will do, browse through, link with, zoom to, experiment with, manipulate, and hypernavigate. Again, the two assumptions discussed with graphics could also be argued as reasonable guidelines for interactivity in simulations. Either give everyone as many options as possible, with as much social interaction as possible, or provide a steadily increasing gradation, so that more mature learners have a wider range of tools, options, and possibilities for collaborative social interaction (even with interaction partners in other countries, through telecommunications-facilitated interaction).

2.6.1 Guidelines for Interactivity: The Ellipse

As before, we do not support either of these as guidelines for interactivity in simulation software. Instead, we see interactivity as premature, perhaps overwhelming or counterproductive near Critical Transition 1, but also perhaps less desirable near Critical Transition 4, where the stage of development of deep understanding in an individual may be distracted by inequities in the comprehensive level of partner interactors, by limitations on time to reflect and speculate, or by constraints on one's imagination imposed by the ideas of the designer of various tool options. Thus, we see the best place for interactivity, either with other students or with a variety of options and tools, as near the "middle" of the cognitive-instructional diagonal, that is, in the area of Critical Transitions 2 and 3. Figure 3 shows our elliptical visualization of guidelines for interactivity in simulations.

2.7 Intelligence and the Critical Transitions

Finally, with regard to embedded intelligence, we also have an hypothesis that can be visualized on the cognitive-instructional grid. This hypothesis, however, corresponds with one of the assumptions we considered and rejected in the cases of visualization and interaction as trends. Our hypothesis with respect to embedded cognitive tools is the "wedge-like" situation, where one's productive use of tools increases with one's cognitive-instructional maturity, relative to the complex system under consideration. Thus Critical Transition 1 may be least appropriate for self-choice and self-use of embedded tools, Critical Transitions 2 and 3 can involve respectively more use of such tools, but Critical Transition 4 offers the greatest possibility for productive use of embedded cognitive tools.

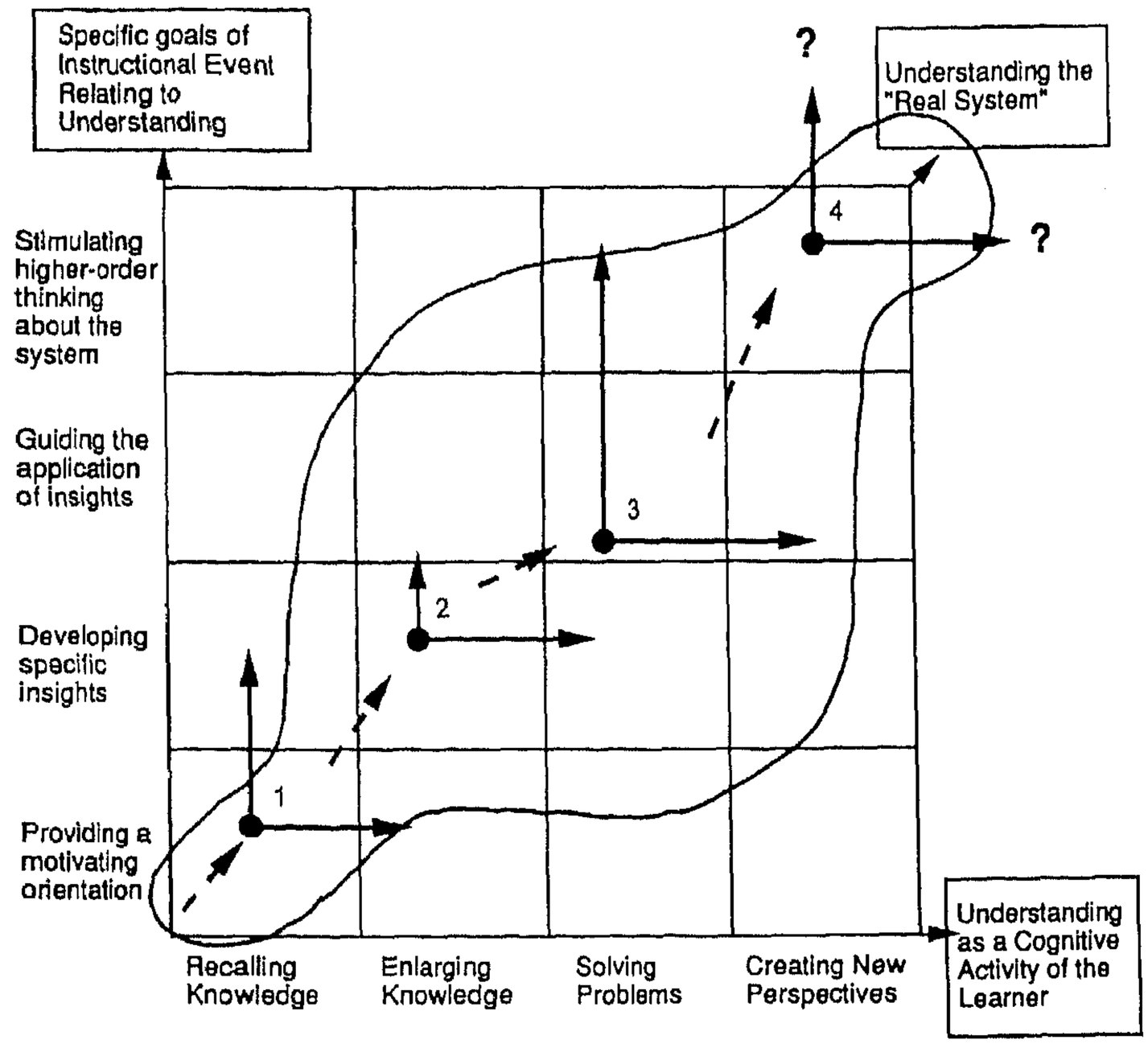

Figure 3 Projection of interactivity trends in educational computer simulations. The wider the ellipse, the more appropriate the instructional integration of rich and complex interactions. It is thus hypothesized that complex interactions may even be counterproductive in the areas of Critical Transitions 1 and 4 but are valuable design options in the areas of Critical Transitions 2 and 3.

2.7.1 Guidelines for Intelligence: The Wedge

Thus we see a wedge as the most appropriate guideline for embedded intelligence in simulation. Figure 4 illustrates this hypothesis. We are less comfortable with this guideline, however, relative to our other guidelines for visualization and interactivity, in that the embedding of more intelligent diagnostic coaching or tutoring probably is best represented by the Ellipse hypothesis associated with interactivity in Figure 3 than it is with the wedge guideline shown in Figure 4. The wedge guideline, however, does appear to relate to intelligent tools such as tools for cognitive mapping or for modelling (see Miller et al., 1993).

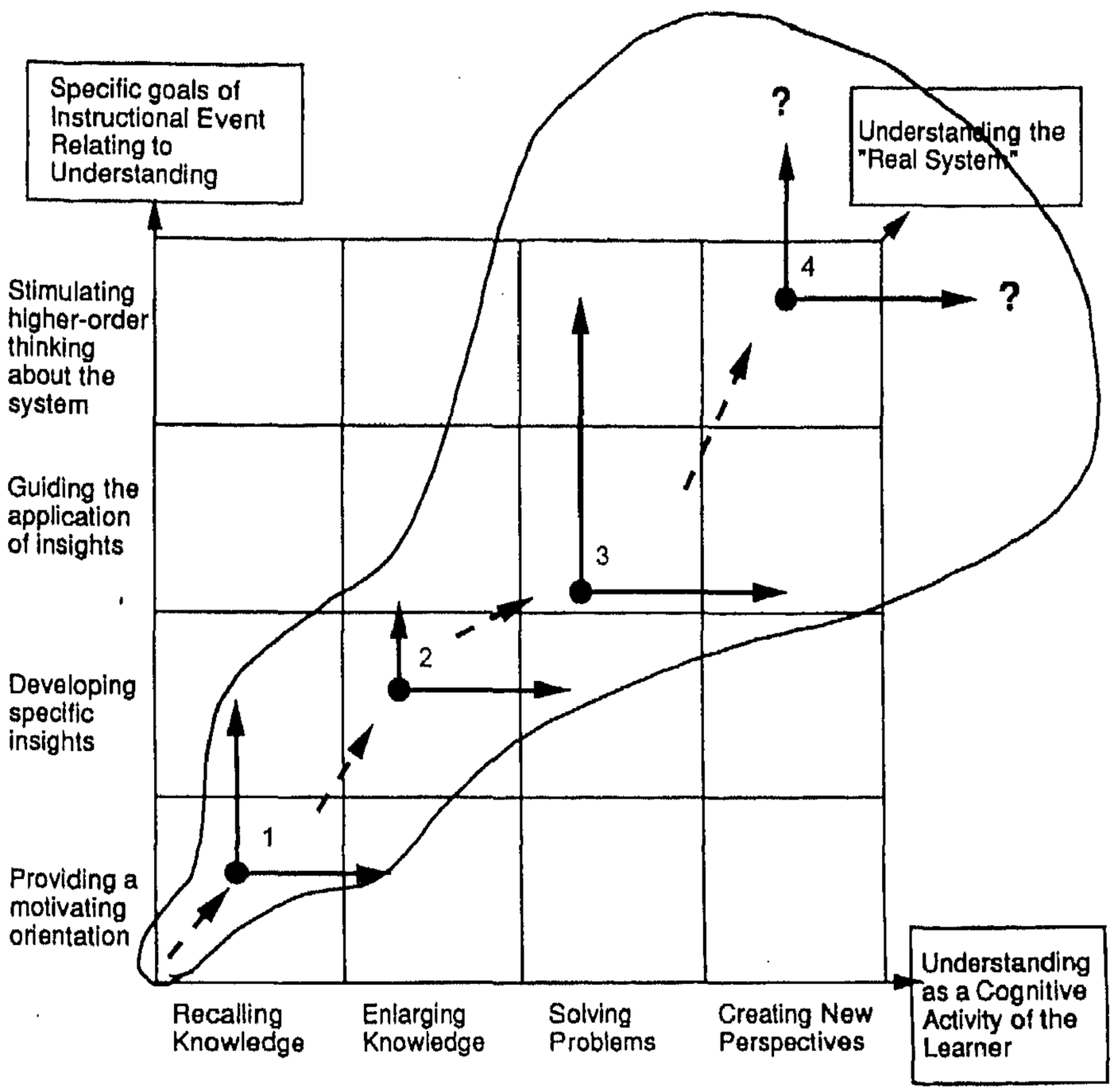

Figure 4 Projection of intelligence trends in educational computer simulations. The guideline is that tools to support metacognitive functioning (i.e., modelling tools and concept-mapping tools) become increasingly more appropriate as cognitive/instructional maturity increases.

2.8 Applying the Trend Analysis to MBLs

So far we have focused on simulations as electronic learning environments with the aim of helping the student better understand complex systems and relationships within those systems. However, we feel that MBLs share relevant aspects of simulations and thus can also be considered relative to the cognitive-instructional grid and our visualization, interactivity, intelligence trends and guidelines. We feel this application to be especially valuable because of the limited attention that has so far been given to the design of the software component of MBL environments. Where do MBLs stand now with respect to visualization, interactivity, and intelligence? What are guidelines for their future development? To address these speculations, we briefly look first at the evolution of MBLs.

2.8.1 Evolution of MBLs

During the beginning of the 1980s, when microcomputers were first being introduced into schools, one of the ideas that challenged teachers' imaginations was the possibility of using the computer for collecting, processing, and plotting data as graphs. This was connected with science and math education and later became a separate direction of research and development with respect to the implementation of computers in educational environments. In the middle of the 1980s many projects involving the use of the computer to capture, process, and display experimental data as graphs were started in the US and also the UK. The main goals of these projects were, from one side, to improve the use of the microcomputer in schools for the above-mentioned goals and activities, but also, from the other side, to explore the educational results and cognitive effects of using computers for science teaching in nontraditional ways, including the idea that computers could augment some of the standard activities in the school science lab.

A landmark project in this evolution was the "Computer as Lab Partner (CLP) Project" (Stein, Nachmias, & Friedler, 1988). This project was designed to examine the cognitive consequences of MBL for various aspects of eighth-grade students' science learning. Each MBL system, used by a pair of students, included an Apple IIe, temperature probes hooked to the computers, and MBL software. Students spent more than half their time performing laboratory activities which investigated thermal phenomena. It was found, among various results, that students improved their ability to identify graph trends and to extract the meaning of the information presented (Linn, Layman, & Nachmias, 1987); and that students' graphing misconceptions were replaced with more accurate conceptions (Mokros & Tinker, 1987).

2.8.2 Visualization and MBLs

Together with the invention of the term, "Microcomputer Based Lab," the educational goals of using MBLs came to be defined more clearly, such as various aspects of the development of graphing skills. For example, students during one of the CLP experiments were to create graphs showing the interdependence among different variables and to see the dynamic relationships between those variables (Linn, Layman, & Nachmias, 1987). This main goal of MBLs was thus connected with some specific and measurable cognitive gains for the learners. Cognitive learning goals came to be further defined, relative to comprehension and manipulation of graph features and graph templates, to graph-design skills and graph problem-solving skills (p. 245–247). It became possible also, together with the visualization of existing physical laws, to make the next step and to interpret already-given graphs, being able to articulate some of the interdependencies between variables, and thus to increase the graph-related problem-solving skills of the students. An example of this is the "Back to the Future" graph approach (Mokros & Tinker, 1987), in which students had to interpret a graph that goes backward in time. This continual refinement of cognitive expectations for interpretation of MBL displays also led to an enhancement

of the requirements for better visualization inside the MBL environment, which in turn led to even more complex cognitive goals, such as evaluation of different kinds of complex information using MBLs. Another study from the Berkeley group involved with the CLP Project, which was devoted to evaluations of science lab data and the role of computer-presented information (Nachmias, & Linn, 1987), illustrates this evolution of visualization in MBLs. The study was directed toward three purposes: "to assess the extent to which students critically evaluate computer-presented graphs, to examine the effect of an extensive use of MBL on students' critical evaluation skills, and to assess the effect of enhanced explicit instruction on the development of these skills" (p. 493). In this study, the instruments for critical evaluation of graphs opened another direction of evolution of MBLs—interactivity.

2.8.3 Interactivity and MBLs

The instrument in Nachmias and Linn's 1987 study was devoted to the analysis of the causes behind five cases of invalid or unreliable graphs: errors in graph scaling, in probe setup, probe calibration, probe sensitivity, and errors occurring through experimental variation. This analysis needed interactivity for its investigation. More work began to occur to increase the interactivity aspects of MBL use, for example through the provision of computer-generated feedback as a design feature within the MBL (Friedler, Nachmias, & Linn, 1988). Not only for increasing the level of interactivity but also for fostering students' thinking skills, the on-line feedback provided by the computer in conjunction with an appropriate instructional environment was expected to foster students' thinking skills. This indeed was also an implicit investigation relating to increasing the "intelligence" of the MBL.

2.8.4 Intelligence and MBLs

The goals in this aspect of Friedler, Nachmias, and Linn's 1988 study were to examine the use of MBLs to foster true scientific reasoning skills, observation, and prediction. There were three activities in this study, all carried out within an MBL environment. These were: "(a) off-line activities and games that introduced the concepts of observation and prediction and their role in the process of problem solving, (b) domain general computer games, and (c) a series of experiments investigating the temperature flow of liquids during heating and cooling." This study also showed that, except for collecting, recording, and manipulating data, the MBLs existing at that time did not in themselves serve other activities connected with knowledge acquisition and processing. Only the operational part of the problem-solving process was supported and improved through the use of the MBLs, but not the higher-order thinking-skills aspect. It will have to depend on what the teacher and student do with the MBL environment that will bring its use into the metacognitive domain.

In the last few years, however, initiatives to enhance the intelligence of MBLs, such as building into the MBLs models for simulation and for system modelling in order to increase the understanding of the system, have begun to appear. New con-

cepts were developed to express trends in this direction—such as The Computer as a Lab Partner Curriculum (Linn & Songer, 1990). As an example of these concepts, an MBL was integrated with a model of thermodynamics in order to provide a coherent explanation for a class of interrelated problems, rather than risk MBL use being associated with isolated understanding of individual problems. This conjunction of MBL and intelligent support tools can come to help the science educator improve science education by focusing not only on fundamentally important knowledge domains, but also on the strategies necessary for problem solving in those domains.

Another good example is the IP-COACH system (see Hartsuijker, Bart, & Zandbergen, 1992), a modular MBL program developed by a team at the Department of Physics Education of the University of Amsterdam. Their original MBL was extended with two modules, CALCSHEET and MODEL-ENVIRONMENT, where the last module is comparable with some existing programs for dynamic system modelling. The MODEL-ENVIRONMENT module allows the student to put in parameters and starting values of variables, which are interpreted in a mathematical model in the form of a differential equation, and later to compare the results received from the simulation model and from the original MBL.

2.8.5 MBLs and the Three Trends: Where Are MBLs Now?

Referring to the three main trends—visualization, interactivity, and intelligence—and projecting the evolutionary process of MBLs, as described above, on the cognitive-instructional grid used earlier for the consideration of educational computer simulations (Figure 1), we offer the conclusion that MBLs at this moment are "in the middle of the road." As a field, we are trying, often successfully, to solve problems and to guide the application of insights using MBLs, but we still have limited experience with moving students to Critical Transition 4—"Create new perspectives/Stimulate higher-order thinking"—within the traditional design of MBL software. That is why, reflecting on the visualization, interactivity, and intelligence trends, and looking for new areas of enlargement and enrichment of the MBL concept, we suggest it is time to rethink some design aspects of MBLs. For example, MBLs frequently assume various limitations (amount of data that can be captured and analyzed, number of dimensions available for graphing interdependencies [MBLs now typically use only two dimensions], etc.). Using the contemporary techniques that are now enriching simulations, we may be able to overcome some of these design limitations in MBL software and thus reach more effectively the desired educational goals. In terms of our construct of the idea of Critical Transitions in educational simulations (Figure 1), the above-described evolutionary process of MBL software appears to be a bottom-up procedure, starting at the origin of the graph and moving "up," toward the middle of the grid, now generally located somewhere around "Enlarging Knowledge" as a cognitive activity and "Developing Specific Insights" as an instructional strategy.

Looking at the same grid but in the framework of the guidelines for visualization, interactivity, and intelligence that we discussed for simulations (see Figures 2, 3, and 4), we interpret this as implying that the current state of MBL software is typified by

relatively simple visualizations (thus most appropriate for Critical Transition areas 2 and 3), not a very high level of interactivity (thus most appropriate for Critical Transition areas 1 or 4), and only a limited intelligence (thus most appropriate for Critical Transition areas 1 and 2).

However, although there is currently an insufficiency or mismatch—of visualization, interactivity, or intelligence in MBL software—work is already underway to try to find ways to balance these insufficiencies. Thus we next turn to what we see as top-down evolutionary processes using multimedia techniques in science teaching. We believe these media-driven techniques may be able to augment some of the inadequacies in MBL software environments from a cognitive/instructional perspective. We call this area of development "Multimedia Labs."

2.8.6 Evolution of MML (Multimedia Labs)

Looking into product descriptions in the latest catalogues of multimedia educational software, we can see technically sophisticated products using video and computer graphics for explanation of basic principles in biology, physics, and chemistry. We call these packages MMLs—multimedia labs. For the accompaniment of experiments, fixed simulation models are recorded on the same videodisc as that where extensive collections of graphical images and video sequences are available. For example, the IBM Biology Series[2] is described as being developed around a tutorial-oriented instructional design, but it includes colour graphics, simulations and animations, as well as support tools such as on-line help and glossary, so that the student can better understand difficult concepts. The package, "Chemical Life Processes Explained," of the IBM Biology Series, is a particular example. It works with the same parameters as many MBLs—pH, temperature, and substrate. The package "Discover by Exploring" (also distributed by IBM) shows how an interactive videodisc can be integrated with such multimedia learning environments. Here the videodisc works with software that guides its use in 30 sequenced lessons. Students can, via the videodisc, observe chemical reactions, plan and carry out kinetics experiments, and be guided as they work through simulated experiments. Students can see the results of their mistakes, watching on video and observing feedback delivered via graphics.

A weakness in these multimedia collections is that the models underlying the simulations used within them cannot be changed; thus the system is described once through a mathematical model, and the student is constrained in his exploration and capacity to simulate and change the system under investigation, to try different alternatives. Instead, the simulation is only of one fixed process. Thus the cost of increased visualization via storage on videodisc or CD-ROM is a limitation on what can be explored in a simulation environment.

There are also examples in the "IBM Physics Discovery Series" which are very similar to the starting point of MBLs, but in a highly visualized version. The package "Applying the Laws of Motion" is an example. (Early MBLs often worked with pH

[2] IBM, Educational Fulfillment Center, P.O. Box 666, Dayton, NJ 08810-9988

or velocity as measured by an ultrasonic sensor, used for the "discovery" of Newton's Laws.) In MML packages such as the discovery series, combining characteristics of both simulations and MBLs, students can build hypotheses as to how changing certain characteristics of a moving object (i.e., a car) affects its performance, but mainly the students can change only one variable (in the case of the car, the time variable).

Following the trends of evolution of MBLs, the MMLs (multimedia labs) are trying also to increase the level of visualization available to the student (see, for example, the use of "Quicktime movies" in the package "Operation: Frog"[3]), or conversely are trying to increase interactivity at the cost of decreasing visualization. The product "Interactive Physics II"[4] is a physics simulation laboratory that allows students to build and model simple and complex experiments by facilitating users to draw and build objects on the computer screen, define physical properties such as mass and velocity for each object, set up and run experimental environments, then save the animations they create as "Quicktime" movies. The need for systems-oriented thinking and explanation in science is of considerable importance during the educational process, and is leading to the development of very complex MMLs such as "Rediscover Science"[5] and "Science 2000"[6]. The former includes a series of lessons organized in separate modules connected with an increasing number of suggested lab activities; ideas for science projects; and reading, writing, and thinking activities. These products are all available stored on a single CD-ROM disk, but the producer suggests supplementing the disk with videotapes available from the vendor, Encyclopedia Britannica. The "Science 2000" package includes two videodiscs and "hands-on manipulative kits" as well as software and a teacher's guide. This kind of bundling is typical for this stage of the evolution process of the MMLs, in that many producers are now trying to include hands-on manipulative kits as part of their multimedia packages, and to break somehow the limitations of the simulation models recorded on fixed storage media (i.e., videodisc or CD-ROM). Indicative of this direction is a research project now in progress at the University of Amsterdam, which connects hands-on MBLs with multimedia using interactive video. This represents an attempt to connect the stronger interactivity elements of the MBLs with the stronger visualization features of MMLs so that the best elements of each can complement the relative weaknesses of the other. From our guidelines related to Critical Transition areas, however, this may not be the best direction of design development, in that we hypothesized rich, moving-video visualizations as best for Critical Transition areas 1 and 4 and interactivity complexity as best for Critical Transition areas 2 and 3.

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[3] Scholastic Software, Jefferson City, MO 65102
[4] Knowledge Revolution Inc., 15 Brush Place, San Francisco, CA 94103
[5] Edunetics Corp., Arlington, VA
[6] Decision Development Corp., San Ramon, CA

2.9 MBLs, MMLs, and Simulations: Mutual Enrichment

We see that the evolutionary processes associated with MBLs and MMLs can fit very well with our theoretical model, not only because of the content of the process of how we build simulation models, but because of the fact that all these types of instrumentation are striving toward the same goal—the better understanding of complex systems and processes in science. In this sense, sometimes it is very difficult to say, for some flexible and open-ended tools used in secondary math and science education, such as "The Explorer Series: Physics and Biology Explorer,"[7] where the border is among simulations, MBLs and MMLs, as they are more and more being integrated together. Especially good examples of these sorts of integrated products with the goals "system-thinking improvement" and "complex-systems understanding" are software packages for environmental education, such as "Biology Explorer: Population Ecology,"[8] "A Field Trip to the Rain Forest,"[9] and "Interactive Nova—Race to Save the Planet."[10] In the area of environmental studies, often it is very difficult to illustrate the complex relationships among the different species that live in an ecosystem. That is why for this type of content area, a product like "Field Trip to the Rain Forest" that includes illustrations showing each species in its natural habitat, but also accompanying books, sets of disks, on-line guides, and data cards providing information about organisms' homes, food, enemies, and friends, can be educationally appropriate. Using all these resources, students can simulate and graph (as with MBLs) food-chain activities and identify relationships between the different organisms. The package "Population Ecology, Discovering Ozone Module"[11] has software for graphing data as well as manipulating simulation models. Many of the environmental packages have video components.

There is still a long way to go from our current levels of simulations, MBLs, and MMLs to the "perfect" science lab. We need the balanced use of all available technological resources to present to the student the richness and dynamic behaviour of the real world in its full complexity. But we also need to use such resources judiciously, as more is not necessarily better in terms of visualization, interactivity, and embedded intelligence in computer simulations, MBLs, or MMLs. Our simple hypotheses of a so-called Figure 8 guideline for visualizations, an Ellipse guideline for interactivity, and a Wedge guideline for embedded intelligence are offered as a contribution to this design problem for simulations, MBLs, and MMLs.

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[7] Wings for Learning, 1600 Green Hills Road, P.O. Box 660002, Scotts Valley, CA 95067-0002
[8] Wings for Learning
[9] Wings for Learning
[10] Scholastic Software, P.O. Box 7502, Jefferson City, MO 65102
[11] Wings for Learning

References

Collis, B. (1988) *Computers, curriculum, and whole-class instruction.* Belmont, CA: Wadsworth.

Forman, E., & McPhail, J. (1989, March) *What have we learned about the cognitive benefits of peer interaction? A Vygotskian critique.* Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco.

Friedler, Y., Nachmias, R., & Linn, M.C. (1988) *Using microcomputer-based laboratories to foster scientific reasoning skills*. Internal paper, Graduate School of Education, University of California, Berkeley, CA.

Gredler, M.B. (1986) A taxonomy of computer simulations. *Educational Technology*, 26(4), 7-12.

Hartsuijker, A.P., Bart, C. van, & Zandbergen, P. van. (1992) *Courseware development and educational research in the Dutch approach to MBL in chemistry education.* Paper prepared for the NATO Advanced Research Workshop, Microcomputer Based Labs: Educational Research and Standards, Amsterdam, 9–13 November, 1992.

Hollan, J.D., Hutchins, E.L., & Weitzman, L.M. (1987) STEAMER: An interactive, inspectable, simulation-based training system. In G. Kearsley (ed.), *Artificial intelligence and instruction: Applications and methods* (pp. 111–134). Reading, MA: Addison-Wesley Publishing Company.

Hoog, R. de, Jong, T. de, & Vries, F. de. (1991) Interfaces for instructional use of simulations. *Education & Computing*, 6, 359–385.

Jonassen, D.H. (1988) Integrating learning strategies into courseware to facilitate deeper processing. In D.H. Jonassen (ed.), *Instructional design for microcomputer courseware* (pp. 151–181). Hillsdale, NJ: Lawrence Erlbaum Associates.

Jong, T. de., & Njoo, M. (1990, September) *Learning and instruction with computer simulations: Learning processes involved.* Paper presented at the NATO Advanced Research Workshop on Computer-Based Learning and Problem Solving, Leuven, Belgium.

Kommers, P.A.M., Jonassen, D.H., & Mayes, J.T. (1991) *Cognitive tools for learning.* NATO ASI Series F, Vol. 81. Berlin: Springer-Verlag.

Linn, M.C., Layman, J., & Nachmias, R. (1987) The cognitive consequences of microcomputer-based laboratories: Graphing skills development. *Journal of Contemporary Educational Psychology*, 12(3), 244–253.

Linn, M.C., & Songer, N.B. (1990) *Teaching thermodynamics to middle school students: What are appropriate cognitive demands?* Internal paper, Graduate School of Education, University of California, Berkeley, CA.

Miller, R., Ogborn, J., Briggs, J., Brough, D., Bliss, J., Boohan, R., Brosnan, T., Mellar, H., & Sakondis, B. (1993): Educational tools for computational modelling. *Computers and Education*, 21(3), 205–261.

Mokros, J.R., & Tinker, R.F. (1987) The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching*, 24, 369–384.

Moonen, J., & Stanchev, I. (1992) *Theory and instrumentation for visual communication in teaching and training.* Internal document, Faculty of Educational Science and Technology, University of Twente, Netherlands.

Nachmias, R., & Linn, M.C. (1987) Evaluations of science laboratory data: The role of computer-presented information. *Journal of Research in Science Teaching*, 24(5), 491–506.

Reigeluth, C.M., & Schwartz, E. (1989) An instructional theory for the design of computer-based simulation. *Journal of Computer-Based Instruction*, 16(1), 1–10.

Scardamalia, M., Bereiter, C., McLean, R.S., Swallow, J., & Woodruff, E. (1989) Computer-supported intentional learning environments. *Journal of Educational Computing Research*, 5(1), 51–68.

Schaick Zillesen, P.G. van. (1990) *Methods and techniques for the design of educational computer simulation programs and their validation by means of empirical research.* Doctoral dissertation, Faculty of Educational Science and Technology, University of Twente, Netherlands.

Songer, N.B. (1989) Technological tools for scientific thinking and discovery. *Reading, Writing, and Learning Disabilities*, 5, 23–41.

Stein, J.S., Nachmias, R., & Friedler, Y. (1988) *An experimental comparison of two science laboratory environments: Traditional and microcomputer-based.* Internal paper, Computer as Lab Partner Project, University of California, Berkeley, CA.

Tennyson, R.D., & Thurlow, R. (1987) Problem-oriented simulations to develop and improve higher-order thinking strategies. *Computers in Human Behavior*, 3, 151–165.

Towne, D.M., & Munro, A. (1989) Artificial intelligence in training diagnostic skills. In D. Bierman, J. Breuker, & J. Sandberg (eds.), *Artificial intelligence and education: Synthesis and reflection* (pp. 291–297). Amsterdam: IOS.

Towne, D.M., Munro, A., Pizzini, Q.A., Surmon, D.S., Coller, L.D., & Wogulis, J.L. (1990) Model-building tools for simulation-based training. *Interactive Learning Environments*, 1, 33–50.