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Model Transparency in Educational System Dynamics

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Abstract

Model transparency is increasingly identified as a positive or even necessary characteristic of system-dynamics-based learning environments, where model transparency is usually identified as providing modified causal-loop diagrams, equations, or verbal descriptions of a model. The theses of this presentation are: (1) Model transparency may be beneficial for *some* educational goals and conditions, but model opacity may be beneficial for others. (2) Model transparency is a continuum (from transparent to opaque) and is multidimensional (for different aspects of a model, such as its variables, stock-flow combinations, and cause-effect relationships). (3) There are many methods of providing information about a model, and these too will depend on the goals and other characteristics of a learning environment. Rather than seeking to prove that model transparency is valuable, system dynamics researchers should be elaborating on how goals and other conditions determine optimal levels and methods of transparency.

Keywords: model transparency, learning environment design

Introduction

Like any field, System Dynamics has its dogmas, those things we are encouraged to believe because most other people believe them, even if proof is lacking. Zaraza et al. (1998) argued against one such dogma, the notion that system dynamics modeling should be applied only to problems, and not to entire systems. Their point was that there are goals or situations in which modeling systems is beneficial. The situation they discussed was K-12 education, when the learning goal is improvement of general thinking and reasoning skills. My interest is another, somewhat newer dogma, the belief that transparent models are better than opaque models in system-dynamics-based learning environments (e.g., Machuca, 2000). This belief may not yet be widespread enough to be considered dogma, but it is on its way. The thesis of this paper begins with the contention that transparency may be sometimes, but not always, beneficial. I suggest that we must consider the entire transparent-opaque continuum as useful, and that the continuum is a multidimensional one. That is, there are various aspects of a model's transparency (or opacity) and various ways to make a model more or less transparent.

I'll begin with a discussion of the claims about transparency. Next I will discuss the various types and characteristics of system-dynamics-based learning environments, with an emphasis on the learning goals of such environments. I maintain that the types and characteristics of a learning environment should dictate the proper levels of transparency for various aspects of a model.

Based on that discussion, I will put forth some hypotheses about the conditions under which greater transparency will be beneficial, the conditions under which greater opacity will be beneficial, the conditions under which average or varying levels of transparency will be beneficial, conditions that probably do not in and of themselves dictate levels of transparency, and some conditions that, although important in a learning environment, we just don't know enough about to suggest proper levels of transparency. In fact, almost all of these, being hypotheses, can be considered at least partly in the last category, meaning that we just don't know enough to be certain.

I will conclude by discussing various techniques for providing more or less transparency, that is, for providing information directly (rather than through learner discovery) about the model. These too must be chosen based on the types and characteristics of learning environments, and we have much to learn about matching such methods with specific types and characteristics.

When a person questions dogma (whether it be dogma in religion, in politics, or anything else) that person often becomes branded as a heretic. Although people with a more revolutionary bent may enjoy being labeled a heretic, I do not. I therefore emphasize at the start that I do not believe greater transparency is detrimental or that those investigating its usefulness are on the wrong track. Quite to the contrary, within the sub-field of system-dynamics-based learning environments, we sorely need more theory and research on the topic. Determining the relationships between characteristics of learning environments and the various types and levels of transparency are essential for assisting designers of learning environments in their decision making.

Current research literature concerning model transparency

The term *model transparency* arises whenever system dynamicists are discussing or designing learning environments. (Note: for brevity I will not always say *system-dynamics-based* learning environments, though that is what I will always be speaking about.) I have lost count of the times I have heard people claim that models "should be" transparent in learning environments. However, while the contention is often spoken, it does not appear that many times in print.

Machuca (2000), Machuca, et al. (1998), and González, et al. (2000) discuss a decade of research and development on what they call transparent-box business simulators. These are learning environments in which the underlying models are made transparent in various ways. Their research has included design of different types of transparency and comparison of transparent-box with black-box (opaque) simulators and with traditional business education methods. Although they primarily deal with learning environments for business education, they include education about social systems as likely to accrue the same benefits from greater model transparency. The types of transparency they design and investigate include provision of causal-loop diagrams, structural equations, and declarative information such as hypertext help for understanding the model. Their main contentions are that black-box learning environments encourage trial-and-error learning, that transparent-box environments are necessary for learning the linkage between model structure and behavior, that awareness of structure improves understanding and decision making, that black-box environments may result in "incorrect" mental models, and that learning with transparent-box simulation-games is a good "middle ground" between learning by actual model building (which most people agree requires much time and practice) and learning with traditional simulation-game environments, which they believe to be ineffective for the above reasons.

Indeed, Machuca and his colleagues provide evidence from a number of projects that for the learning environments they created and compared, model transparency was beneficial. While I readily accept the evidence that in their research studies there is evidence in favor of model transparency, I take issue with some of their contentions and with the generalizability of their findings.

First, the learning that occurs with black-box simulators is not necessarily trial-and-error learning. The term trial-and-error has an unfairly negative connotation to it. As will be discussed below, there are many good learning environments which seek to encourage discovery learning, guided discovery learning, or scientific discovery learning, and which definitely do *not* aspire to trial-and-error learning (e.g., de Jong & van Joolingen, 1998; Vavik 1995). The creators of those environments would say that trial-and-error learning is what you get when you do not design your environment well, or do not guide your learners well. Such designers intentionally create black-box simulations in order to encourage the learning of research techniques such as the experimental scientific method, and *not* to encourage trial-and-error learning.

Second, although the authors mostly discuss and have designed business learning environments, they have made some small claim to the applicability of the findings to learning of social systems. I find this a dubious contention as there are many differences (as well as similarities) between business systems and social systems. Just one example is that business success depends on competition (certainly between businesses, and sometimes even within businesses) while social systems rely more on cooperation. Are learning competitive and cooperative relationships, which are almost diametrically opposed, both fostered by model transparency? I don't know the answer, but it is an important one to raise and investigate. My point being that generalization from business systems to social systems is by no means automatic. The same is true for many other areas of study for which system dynamics is useful, such as the physical and biological sciences.

Third, the authors conclusions are sometimes a little stronger than their results permit. For example in González, et al. (2000) their conclusions claim "effortless self-learning." Although the authors may believe they have observed effortless learning, they present neither hard nor anecdotal data in support of that contention. I suspect this may be expecting too much benefit from model transparency, and that effortless learning is an exaggeration.

Fourth and last, although I will agree that transparency of models will probably foster understanding of structure-behavior relationships, I am less confident that transparency will foster decision making in real organizations and systems. Why? I believe model transparency will only foster good decision making to the extent that the model learned is the *correct* model in reality. But most system dynamicists agree that models are theories and are always simplified descriptions of reality. If that is so, good decision making will not follow from learning *the* *particular model* depicted in a learning environment. Rather, it will follow from transferring the experience in the learning environment to the *real* environment, and ultimately, learning the *real-world* model, which will not be a transparent one. In other words, I believe that good decision making will follow from learning to interact with and learn models in general, not from learning *particular* models.

In another series of reports (Größler, 1997; Größler, 1998; Größler, et al., 2000) Größler and his colleagues also contend and investigate the notion that model transparency is a beneficial characteristic of learning environments. Their belief is quite similar to that of Machuca, that transparent-box simulators are a good compromise between the ideal learning environment (building models) and poor learning environments (black-box simulators). To his credit, Größler (1997) points out that there are probably circumstances where transparency is *not* desirable. He identifies simulations for *assessment* (rather than for instruction) as being such a circumstance. Thus, he makes the important point that the value of transparency depends at least on your goals or purposes.

Größler conducted an experimental study comparing a transparent-box simulator with a black-box simulator. However, the results were mixed, and hardly convincing of the value of model transparency. There are several explanations for this, including why their results were not as strong and convincing as those in the Machuca research.

The first possible reason is that the methods of providing transparency might not have been as effective for learners as the methods used by Machuca. The simulation used by Machuca provided learners with causal-loop diagrams, structural equations, and a hypermedia help system. The simulation used by Größler provided learners with a verbal description of the model and/or (depending on the experimental condition) a help system which provided causal-loop diagrams and other information. But Größler reported that learners did not use the help system very much, so exposure to the transparent model was, for most learners, only a verbal description. It is certainly plausible that a verbal description is not as effective as a causal-loop diagram in conveying the complexity of a system dynamics model.

The second possible reason is that there appeared to be a procedural flaw in the research activities. Learners were given two goals: do as well as you can in the simulation-game (that is, try to win), and learn as much as possible about the system. The problem is that these two goals are partly incompatible. To learn as much as possible about the system would require intentionally making choices which lead to *poor* business performance as well as making choices that lead to good business performance. To be successful in the game requires you only make good business decisions. In general, this is one of the problems with gaming activities. When you call something a game, people naturally want to win. The goal of winning constrains learners from exploring negative decisions, variable values, and pathways. If you want learners to explore both good and poor decisions and values, it is better to call it simply a simulation (not a simulation-game or a game) and to strongly encourage such exploration. Gruber et al. (1993) describes this difference as the goal of *acquiring knowledge* about a system versus the goal of *gaining control* of a system, and contends that (as may have been the case in the Größler study) learners must often choose between these somewhat incompatible goals. Gruber also suggests that the first goal (understanding) is facilitated more by *specific exploration* (single variable manipulation as in a simple experimental method) while the second goal (control of the system) is facilitated more by *global exploration* (varying multiple variables simultaneously, as is common in gaming activities). It is very possible that the learners in Größler's study took the goal of winning more seriously than the goal of fully understanding, and in doing so weakened any benefits that might have accrued from transparency. I say that there *appears* to be a procedural flaw in the study because it depends on the exact directions to learners and what they subsequently did. If the learners were told to *first* learn as much about the system as possible and to *subsequently* do as well as possible in the simulation-game, and if learners followed such a directive, there might be no problem. But more likely the learners were given the two goals as parallel ones, and as a result were forced to choose one or the other.

The third possible reason, and the last I will suggest, is that the results must simply be taken as evidence *against* the transparency hypothesis (i.e., that greater transparency generally fosters learning in simulation environments). Researchers do not willingly give up hypotheses they believe in, but when the evidence is not there we should always consider the possibility that our hypotheses are incorrect.

The work by the Machuca and Größler research groups are laudable and represent the main efforts to experimentally assess the effects of transparency on learning. Despite the small amount of experimental research, the claims in favor of transparency are often heard within the system dynamics community. Furthermore, both of these research groups clearly believe in the value of greater transparency. There has been no opposition research. That is, there has been no research among system dynamicists hypothesizing conditions under which *greater opacity* is beneficial.

Types of system-dynamics based learning environments

To begin a consideration of how to decide and design proper levels of transparency, I first consider the different types of learning environments that are based upon system dynamics methodology. Maier & Größler (1998, 2000) have suggested a categorization of simulation software to support learning. One major category is model building software and correspondingly, one type of learning environment is that in which people learn by doing system dynamics modeling. This occurs not only in the various higher-education programs on system dynamics, but in K-12 curricula as well (e.g., Mandinach & Cline, 1994; Zaraza & Fisher, 1999; Feurzeig & Roberts, 1999; Jackson et al., 1994). Both (higher education and K-12 curricula) typically have learners analyze and modify existing models (those created by other people) as a first step towards creating and refining their own. A high level of transparency is clearly a part of such environments. But they are not the main focus of the transparency hypothesis. Rather, the focus of the transparency hypothesis is on learners using previously constructed simulations and simulation-games, which is common in many fields of study (business, economics, sociology, military training, physical sciences, biological sciences, and psychology, to identify only the most common). Many, though not all such learning environments, are created using system dynamics software and methods. Many of those that do not, nevertheless include simulation models that are very similar to system dynamics models. Some are quite different, being models based on discrete methods (statistical models) or logical (if-then) rule systems, although in many cases they could have been created using modern system dynamics modeling software as easily as other types of modeling software. More importantly, such simulation and/or gaming environments are of two main types (a distinction not well addressed in the Maier

& Größler taxonomy), expository environments in which the simulation or game presumes to teach the model and provide various types of interactive practice with it, versus discovery environments in which the simulation or game provides opportunities for learners to investigate (i.e., do research on) the system and construct their own understanding of it, and presumably other systems like it. The first type, expository environments, are typical in tertiary and professional environments, especially for endeavors where risk and competition are critical to successful performance, such as business and military education (e.g., Keys, 1997). The latter type, discovery environments, are more common in elementary through tertiary education in subject areas which include scientific and logical thinking, doing research, and solving problems, such as the physical, social, biological, and psychological sciences (de Jong & van Joolingen, 1998; Vavik 1995).

The distinction between expository and discovery learning environments will be discussed more in the next section. At this point I will suffice to summarize by pointing out that the type of environment, expository versus discovery, is crucial to deciding and designing the proper level of transparency.

Critical characteristics of educational environments

We all have a tendency to organize and describe the world in terms we are familiar with. For that reason, it is easy for people in the system dynamics community to emphasize certain types of learning environments (primarily the more expository ones), subject areas (such as business and social policy), educational goals (such as operating in complex competitive environments), and learners (primarily adults). These are reflected in the research on transparency (such as Machuca et al., 1998 and Größler et al., 2000) and the taxonomy of simulations by Maier & Größler (1998, 2000). But we should frequently remind ourselves that the world is bigger and more diverse than our particular sphere of interest and activity. In that regard, system dynamics is increasingly being used to create learning environments for children and young adults (Mandinach & Cline, 1994; Zaraza & Fisher, 1999; Feurzeig & Roberts, 1999; Jackson et al., 1994), to create scientific discovery learning environments (Alessi, 2000; de Jong & van Joolingen, 1998; Vavik 1995), and to do so for a wide variety of subject areas and educational goals. It is therefore important for us to generate a theory of transparency and guidelines for transparency design that are *sufficiently broad* to encompass the variety of learners, goals, subject areas and other learning environment characteristics that are in play throughout the larger world of people using educational simulations and games, especially those based upon system dynamics models. Towards that end I now discuss the characteristics of learning environments that are probably the most important for transparency design.

Goals. One of the most important characteristic of a learning environment is the learning goals. These include: (1) The specific subject areas. (2) Learning a process (such as research and exploration). (3) Learning specific content (such as principles of economic theory). (4) Learning skills (such as competitive behavior, cooperative behavior, or individual diagnostic skills). (5) Initial learning. (6) Transfer of learning to a real-world work or other environment (Cormier & Hagman, 1987). (7) Learning a particular system or problem structure and behavior. (8) Learning generic skills such as thinking and problem solving. (9) And in some cases non-learning goals, such as using a learning environment to facilitate model validation.

Let me elaborate on two of these. Concerning Number 2, a large number of educational simulations are of the Scientific Discovery Learning variety (de Jong & van Joolingen, 1998). These are quite common for learning principles and theories in the physical, social, and biological sciences, including elementary, secondary, and tertiary education environments. The goal of such environments is for students to learn not only science content, but also learn science process, such as experimental and observational methodologies. Many such simulations are or can be constructed using the system dynamics methodology. This is a goal which, as I will discuss below, will likely require *less* transparent models for the goal to be realized.

Number 9 is an interesting and important goal pointed out to me by Pål Davidsen of the University of Bergen. Validation of models is a critical endeavor, but content experts and other stakeholders (such as business executives) have little patience for analyzing stock-and-flow diagrams or structural equations. However, the same people are quite often motivated to participate in networked simulations or games based upon a business model or problem of interest to them. Thus, a learning environment can be a powerful technique for involving such experts or stakeholders deeply in the model validation process. In contrast to goals of type 2 (the paragraph above), this type of goal is likely dependent upon a very *high* level of model transparency.

Learner characteristics. Another critical characteristic of the learning environment is the characteristics of the learners themselves (Weller et al., 1995). This includes age, prerequisite skills (such as reading, computer, and mathematical skills), prior knowledge and experience in the subject area, tolerance to cognitive load, motivation, learning preferences (such as whether they prefer learning from visual materials versus verbal materials), and cognitive styles (such as the frequently researched styles called field dependent and field independent). Most of these (age, experience, motivation) are fairly common and obvious. I will discuss a few of the less obvious ones.

Cognitive load theory (Kashihara et al., 2000; Kirschner, 2002) is based on extensive research demonstrating that all human capacities are limited and that when overloaded, problems result. This is true for sensory perception, encoding of what we perceive, memory, and thinking. Since system-dynamics-based learning environments typically deal with complex systems and problems, they are likely to place high demands on learners' memory and thinking, with the possibility of failure to learn what is intended. Of particular importance here is not whether transparency versus opacity place greater load on memory and thinking activities, but what *types* of transparency place greater or lesser load. This will be discussed soon.

Although many types of learning preferences and styles have been suggested and researched, one of the more widely accepted is the distinction between visual learners versus verbal learners (Richardson, 1977). While it may be possible that this learning preference correlates with successful levels of transparency, it is more likely (as was also suggested for cognitive load theory) that it correlates with what *method* of providing model information (transparency method) is used. For example, stock-and-flow or causal-loop diagrams may be much more effective for visual learners, while tutorials, lectures, or other verbal explanations may be more effective for verbal learners. This is one of the potential advantages of learning with multimedia, namely, that providing model information using a combination of symbol systems (e.g., pictorial, textual, auditory) will afford different types of learners with the features they each require for success.

Educational philosophy. Although it has not yet been an issue in the field of system dynamics, the fields of K-12 and tertiary education have been, for the last decade, deeply engrossed in arguments about educational philosophy. The arguments relate epistemology to educational techniques, and are embodied in the contrasting philosophies of objectivism and behaviorism on one hand, versus constructivism and social constructivism on the other. The objectivist school of thought emphasizes more expository learning environments while the constructivist school emphasizes more exploratory and productive learning environments (e.g., Harper et al., 2000). Interestingly, both schools of thought are represented in the system dynamics community. The notion of learning by creating system dynamics models is a very constructivist one, and the movement to improve K-12 education through system-dynamics-based curriculum approaches represents a way of infusing more constructivist environments into traditionally very objectivist classrooms. On the other hand, the viewpoint that model transparency facilitates learning in simulation-gaming is a somewhat objectivist one, while favoring black-box simulations such as in scientific discovery learning is a more constructivist one.

Most educators, of course, do not adhere strictly to one philosophy or the other. Rather, they are somewhere in between, though often espousing a greater affiliation with one point of view or the other. Most educators combine objectivist and constructivist techniques, depending on the learners, content areas, and specific goals. This is in keeping with my contention that the choice and design of model transparency should depend on the learners and goals.

Curriculum sequence. A characteristic of the learning environment similar to and related to educational philosophy is curriculum sequence. Curricula have long been characterized as being either top-down (meaning they start with the big picture and progress to greater and greater detail, typical of many science curricula) or bottom up (starting with details and building progressively to the bigger picture, as is typical in traditional school mathematics programs). Another type of curriculum sequence is the *spiral curriculum* (Bruner, 1960, 1966), which is more recently reflected in Reigeluth's (1979, 1992) *elaboration theory of instruction*. Though more top-down than bottom-up, these approaches recommend multiple passes through the content area, each time elaborating the details, complexities, and arguments of the field. Recently, within the context of science education, White (1993) has recommended what she calls a *middle-out* sequence (in contrast to either top-down or bottom-up). Rather than either the analytic approach of traditional science curricula, or the hands-on laboratory approach of some newer science curricula, White recommends *discrete step* computer simulations which are very similar to system dynamics models, and which could easily be created using system dynamics software. As with all of the learning environment characteristics I am discussing, the curriculum sequence has implications for the level of model transparency and the techniques used for providing that level of transparency.

There are many other characteristics of learning environments that could be enumerated and discussed. Given limitations of space, I will end this section with consideration of two related characteristics: the extent to which unknown or incomplete information is an essential part of the learning environment, and the extent to which risk or risk-taking is part of the learning environment. Clearly these are related. A common reason for risk is incomplete or unknown information. Competitive business simulations are an example where incomplete or unknown information is not only present, but an essential part of the learning goals, because they are present in the real-world business environment and students must learn to deal with them. Risk is involved in many aspects of business education, such as investment strategies and long term planning. It is also present in social sciences such as psychological simulations, because human behavior is not strictly deterministic and predictable, but rather, is statistical and sometimes includes elements of randomness. The necessity of including unknown or incomplete information may preclude the use of very transparent models (which by their nature tend to make information visible and therefore known). The issue of risk is similar but more complicated, as a model may be completely visible, but still include statistical or probabilistic parameters which show that risk is involved without eliminating the need for risk-taking behavior.

Having discussed some of the more important characteristics of learning environments with regard to the issue of model transparency, I will now suggest some hypotheses about the conditions under which greater transparency may be beneficial, versus the conditions under which greater opacity may be more beneficial. I will also discuss those characteristics which are more complex (for example, which might suggest intermediate levels of transparency or dynamically varying transparency), those which in themselves do not strictly suggest levels or types of transparency, and those which we know little about and which clearly require research.

Conditions under which greater transparency may be more beneficial

This and the next few sections must be recognized as hypotheses about transparency, not rules to be followed. As such, they are hypotheses that deserve more research. But such research need not only be done in experimental laboratories. The design and development of learning environments is itself a cyclic and empirical process. The designer of a learning environment can begin the design process from these hypotheses and create a prototype environment based upon them. The designer must then subject the prototype to evaluation with appropriate learners and modify the environment, including modification of model transparency levels and techniques, based on the evaluation data collected. These hypotheses are based in part on the research discussed above, in part on practical experience in instructional design, and in part on common sense. With this caveat in mind, following are hypotheses for the conditions under which greater levels of transparency may be more beneficial.

In the previous discussion, and in the hypotheses which follow, it should be noted that I (like other authors) have used transparency in two ways. I use it to label the entire continuum, with high transparency at one end and low transparency (opacity) at the other. But the term transparency is also used for one end of the continuum. For clarity, therefore, I will use the single word *transparency* to refer to the entire continuum, and when used in that fashion it is neutral, that is, not indicating a high level of transparency. In contrast, when discussing the ends of the continuum, I will use the phrases *high transparency* or *greater transparency* for one end, and *lower transparency* or *greater opacity* for the other end.

Business simulation-games ***without*** *unknowns*. There are many types of business simulations and games (Keys, 1997). In some, such as management of manufacturing resources, unknown or incomplete information is not very important. The intentional presence of unknowns obviates the value of greater transparency. But business simulations and games which do *not* incorporate unknowns as an essential component probably benefit from greater transparency.

Expert or advanced learners. Older learners, those with greater cognitive abilities, or those with more experience and background knowledge in the content area have a greater capacity for complex information and, similarly, greater tolerance for cognitive load. They are better able to understand causal-loop diagrams and perhaps even stock-and-flow diagrams. They have a better understanding of the very notion of what models are. Thus, they can benefit from greater transparency and are less likely to be confused by it. Learning is likely to be more complete and more efficient for them with higher levels of transparency.

Instructors with more objectivist or behaviorist philosophy. Learners are not the only people in educational environments and it is not only their characteristics which influence outcomes. Success of a learning environment depends on the instructors or facilitators as well as on the designers and students. Instructors with a more objectivist or behaviorist philosophy will probably be more accepting of transparent models and prefer their use. Design of learning environments can take such instructor characteristics into consideration by creating a variety of materials suited for different types of instructors. For example, a learning environment can be designed which includes more transparent-model simulations for instructors with a more behaviorist or instructivist epistemology, and more opaque-model simulations (though for the *same underlying model*) for instructors with a more constructivist epistemology.

Top-down curriculum sequence. If the learning environment is being created for inclusion in an already existing curriculum, the sequence of that curriculum will probably be already determined, and should be considered in designing the level of transparency. If the sequence is a top-down one (beginning with the big picture and progressing to successively greater levels of detail) a learning environment with more transparent models will probably fit in better, especially at the *beginning* of the curriculum. A causal-loop diagram, for example, might be appropriate because it is a top-level explanation, showing the overall structure in general terms. Note, however, that the level of detail included in a causal-loop diagram can vary, so if it is introduced as a top-level explanation, showing only the more important variables in a model might be appropriate.

System dynamics curricula. When the goal of a curriculum is specifically learning about the system dynamics approach, greater model transparency is generally indicated. This condition probably does not need much explanation. Not only is understanding models an objective of such a curriculum, but the learners will already be familiar with several methods of providing model transparency (causal-loop diagrams, stock-and-flow diagrams, model equations) and will be capable of analyzing them without specific instruction each time they are used. Both efficiency and depth of learning can thus be achieved.

Learning particular models with high validity. Many models are theories or have not yet been well validated. In those cases, we should be wary of implying to learners that the model is a *correct* one and should be learned in its explicit details. But sometimes we have high confidence in a model, or even if we do not, we want students to learn *that* particular model or theory to a high degree of proficiency. When a *particular model* is the primary learning objective, high transparency is probably appropriate. Furthermore, the greater the known validity of a model, the higher the transparency can reasonably be.

Validating models through simulation-gaming. As discussed earlier, simulation-games may be used to motivate content experts and stakeholders to engage in model evaluation and validation. When that is the purpose, a very high level of transparency is necessary, because users must be able to see a model in all its details in order to adequately critique and improve it.

Learning to control a system or problem. As discussed earlier (Gruber et al., 1993) a learning environment may have the goal of learners *understanding* a system or problem, or becoming skilled in *controlling* a system or problem. When the goal is controlling, such as running a particular business successfully, greater transparency is probably better. A similar situation is diagnostic simulations (Johnson & Norton, 1992). These are instructional simulations teaching how to determine and fix problems, such as a malfunctioning car engine or a sick patient in the hospital. Being able to diagnose a problem generally requires a good understanding of how the device (or organism) operates. Therefore, model transparency is likely to benefit such simulations. An interesting example of this is the popular Beer Game. Even when users are exposed to the model, the still have difficulty controlling the system because they have not internalized the dramatic effect of delays into their own mental models.

Conditions under which greater opacity may be more beneficial

I turn now to some hypotheses for conditions under which less transparency, or greater opacity, is likely to be better. My explanatory remarks in this section are briefer because many of these hypotheses are essentially the opposite conditions as those of the previous section. For example, if a more objectivist/behaviorist educator will prefer greater transparency, the other side of the coin is that a more constructivist educator will prefer greater opacity, preferring the learners to engage in research and determine the relationships on their own, rather than being told them.

Sciences and other subjects which benefit from discovery learning. The scientific discovery learning approach is very popular in science education, including physical, social, and biological sciences. It combines learning of specific content with learning of scientific methods. Because the scientific discovery learning approach explicitly requires learners to do research on models and determine their structure for themselves, transparent models would run counter to the very goals of this approach. This method depends on the use of more opaque models. The goals of scientific discovery learning include not just learning the principles, but also learning the process of coming to understanding those principles. Such goals emphasize depth more than efficiency.

Business simulation-games ***with*** *unknown or incomplete information*. Standing in direct contrast to business simulation-games *without* unknowns, those *with* unknown or incomplete information require lower transparency in order to keep information intentionally unknown or incomplete. Similar to scientific discovery learning, such simulations by their very nature depend on a greater level of opacity. For example, a business game in which you do not know the number or nature of your competitors depends on a greater level of opacity.

Novice learners. In direct contrast to expert learners (who tend to benefit from transparency) novice learners (younger learners, those with little experience or knowledge of the subject, those with less ability in the subject, or those with little experience in system dynamics) will have less tolerance for the cognitive load created by model transparency. Though this suggests lower levels of transparency, more importantly it suggests transparency *techniques* which are lower in complexity and which demand less prior knowledge. Novice learners would have particular difficulty with methods of displaying transparency such as equations or causal-loop diagrams. However, they may benefit more from techniques like verbal (including aural) explanations.

Instructors with a more constructivist or social-constructivist philosophy. Educators with a more constructivist philosophy prefer to have students learn by exploring and doing research themselves. They are likely to be more comfortable with opaque models, believing that they do not "give" students the information, but instead foster the learners' own inquiry and search for knowledge (e.g., Harper et al., 2000).

Generic learning such as to develop general thinking and problem solving skills. When the learning goals emphasize generic skills and abilities (in contrast to specific subject area content) that are to be transferred to a variety of content areas, inquiry approaches are generally considered more fruitful and simulations with more opaque models are likely to be more beneficial. This is an example of far transfer, or generalization (Clark & Voogel, 1985). That is, the main goal is learning skills that can be applied to a number of subject areas, such as problem solving or analysis skills. The more transparent a model is, the more learning will tend to focus on the particular model (and its structure) being considered. The more opaque a model, the more learning will focus on the skills of analyzing and using models in general. Such general learning skills include observation, experimental method, creative problem solving, design, and the like.

Understanding a system or problem. In contrast to *controlling* a system or problem is *understanding* the system or problem. Gruber et al. (1993) argues that understanding a system or problem benefits from what he calls *specific exploration,* such as systematic variation of just one variable at a time. Specific exploration is likely to be facilitated by *less* transparent models, because more transparent models will encourage the learner to modify several variables simultaneously, as is typical in simulation-game environments.

Operating a device. An important category of educational simulation includes those teaching how to perform a procedure or operate a device, such as driving a car. Earlier I identified one type of procedural simulation, the diagnostic simulation (Johnson & Norton, 1992) as being likely to benefit from higher levels of transparency. However, many procedural simulations deal only with operating a device under normal circumstances, not diagnosing or fixing problems (Pappo, 1998; Towne, 1995). For example, just as driving a car does not require an understanding of how the internal-combustion engine works, most such procedural simulations will not benefit from high levels of transparency. Little understanding of the model is required, so higher opacity is dictated.

Conditions under which average or variable transparency may be more beneficial

It was suggested that top-down curriculum sequences may benefit from higher levels of model transparency. In contrast, bottom-up, middle-out (White, 1993), or spiral curriculum sequences (Bruner, 1960, 1966) might benefit from average transparency (about half-way between highly transparent and highly opaque) or from dynamically varying levels of transparency. Curricula based on the elaboration theory of instruction (Reigeluth, 1979, 1992) are similar to Bruner's spiral curriculum approach and may benefit from average or varying levels of transparency as well. The notion of dynamically varying transparency is comparable to the idea of dynamic *fidelity* (Alessi, 1988; Alessi & Trollip, 2001), which various simulation researchers have suggested is a way to provide novice learners with less complex learning environments (to facilitate initial learning) and advanced learners with more complex and realistic learning environments (to facilitate transfer of learning). Similarly, initial learners in a system-dynamics-based learning environment may benefit from the lower cognitive demands of a less transparent model, while more advanced learners will benefit from more transparent models. As a particular learner progresses from being a novice to becoming more expert, gradually increasing transparency may effectively match the learner's needs and cognitive load capacity.

Conditions that do not dictate transparency in and of themselves

Some of the important characteristics of learning environments that were discussed earlier may not *themselves* dictate appropriate levels or types of transparency. That is, they will only suggest such levels and types when considered in *conjunction* with other characteristics, such as the learners' characteristics, the educational philosophy, or whether learning is expository versus discovery. Characteristics which probably do not in themselves dictate transparency are the subject area (because almost any subject area is likely to include situations where transparency is valuable, and other situations where opacity is valuable), emphasis on initial learning versus near transfer of learning (Clark & Voogel, 1985; Cormier & Hagman, 1987; Detterman & Sternberg, 1993), and when risk or risk taking is an important part of the curriculum. A good illustration deals with the last characteristic, risk taking. Learning about risk taking in competitive business environments probably will benefit from high transparency, whereas risk taking in operating a device, such as driving a car, probably does not. The first type of risk taking deals with making good decisions based upon available evidence, and that likely includes an understanding of how the business environment (the model) is structured and behaves. In contrast, the latter type of risk taking is really attitudinal learning (that is, an attitude towards driving safely) and does not depend as much on understanding the model structure or behavior.

Conditions that require more research concerning their impact on transparency

For some conditions (such as whether learners are field dependent or independent, or are highly motivated versus unmotivated) we are barely capable of generating likely hypothesize as to whether high or low transparency will be beneficial. No good logical case can be made for either high or low transparency or for different methods of transparency. Or conversely, good cases can be made for *either*. Take, for example, the characteristic of learners with low motivation. We can make the case that learners with low motivation are likely to have low capacity for cognitive load as well, and will therefore benefit more from opacity. On the other hand, we can make the case that low motivation learners place greater value on efficient learning of specific objectives than on learning generalized skills, and that would dictate higher transparency. More developed theory and research is needed to provide advice. Lacking that, developers must make decisions based on their own experience and then evaluate the effectiveness of their decisions through pilot testing, making modifications according to the evaluation outcomes. That of course is what systematic instructional design is all about, using an empirical approach in which a prototype learning environment is created, subjected to assessment with real users, and modified repeatedly until the testing demonstrates that the learning environment meets its objectives.

Having discussed the characteristics of learning environments and how they may influence design of model transparency, I now discuss *types* of transparency and how decisions about such types will depend upon the characteristics of learning environments.

Techniques for providing various levels and types of model transparency

First, we should remember that when discussing transparency we are referring to a design continuum with high transparency on one end and low transparency (or high opacity) on the opposite end. Furthermore, different aspects of a model may be more or less transparent. That is, a learner may be shown or informed of the primary variables (e.g., stocks and flows), all the variables (including converters and constants), the cause-effect relationships, the formulas attached to particular variables, special functions (such as delays), model sectors, and so on. A novice learner, for example, might be shown only primary variables and cause-effect relationships, while a more advanced learner might be shown much more. That having been said, what are the *techniques* by which parts of a model may be explicated for the learner, or made transparent? The list is long and I will only discuss some of the major ones. A fairly complete list (including techniques which overlap to some extent) would include: visual methods, verbal methods, auditory methods, colorization methods, animation, causal-loop diagrams, stock-and-flow diagrams, structural equations, tutorials, video, schematic diagrams, cognitive maps, coaching and advising systems, expert systems, hypermedia reference material, on-line help, collaborative learning methods, cognitive scaffolding, cognitive apprenticeship, and electronic performance support systems.

Clearly, space does not permit discussion of all twenty techniques listed above. I will comment on the first ten and how learning environment characteristics inform their design.

A major distinction may be made between visual (meaning pictorial) methods, verbal methods, and auditory methods. Diagrams such as causal-loop diagrams are primarily visual methods while a textual description of a model and its structure is primarily verbal. Auditory methods may be verbal as well, such as a spoken (rather than textual) description of a model. Auditory methods may be non-verbal, such as sound effects depicting behavior (a rising or falling variable, loop dominance, and the like). Of particular importance is that learner characteristics interact with visual, verbal, or auditory methods. Some learners prefer or better understand pictorial descriptions while others benefit more from verbal or auditory methods. Extremely complex models benefit more from visual methods. Changing conditions or sequences are sometimes depicted best with sound (Fleming & Levie, 1978, page 47). Learners with physical disabilities (especially visual or auditory ones) may be restricted to particular methods, which suggests that a combination will be beneficial for a variety of learners. This last consideration suggests an important overriding consideration, that when greater model transparency is dictated, a combination of methods is likely to be more effective than just one.

Colorization is a specific visual technique worth mentioning because of its special advantages and disadvantages. Colorization cannot itself make a model transparent, but it can make specific *aspects* of a model more transparent, such as loop dominance, variables which directly influence a particular variable, variables undergoing the greatest rate of change at a particular time, variables which are increasing (in black) versus decreasing (in red), and so on. For example, in Machuca et al. (1998), when a learner pointed at a variable in a causal-loop diagram, a change in color of the cause-effect arrows highlighted all the other variables which affect the one the learner was selecting. Advantages of color techniques are that they can be clear even to young or novice learners, help decrease cognitive load, and are good for top-down approaches (because color helps demonstrate overall characteristics of a model). Of course, colorization is generally used in conjunction with other visual approaches, such as causal-loop diagrams or structural equations. As for disadvantages, because color blindness is a common disability, human factors specialists generally recommended that color be used as a redundant cue (Shneiderman, 1998, pp. 398-402). That is, color should be used *in conjunction with* numeric, auditory or other information conveying the same concept, even if the other methods do not convey the information as nicely as color. Shneiderman (1998) discusses the advantages versus disadvantages of color and useful guidelines for its effective use, such as providing users the ability to toggle color coding on and off.

Like colorization, animation is usually used in conjunction with other visual techniques such as causal-loop diagrams. However, animation of pictures (in contrast to diagrams) may also be used to depict the increasing or decreasing size of variables, changes in flow, and cause-effect activity. Simplified animation may be much easier to comprehend than traditional system dynamics diagrams, and thus better for younger or novice learners, or to simplify very complex models even for advanced learners.

Causal-loop diagrams (frequently augmented with other visual techniques, such as small graphs showing reference behavior or colorization to emphasize cause-effect relationships) are one of the favorite methods of making models transparent. They convey much more information than verbal descriptions, yet are easier to understand than stock-and-flow diagrams. They especially make the variables and cause-effect relationships transparent, though alone they do not make the mathematics of the variables visible. They are good for moderately experienced learners and in circumstances were a fairly high degree of transparency is desired. They are good at making the big picture clear, but less valuable for the details (for which stock-and-flow diagrams or structural equations tend to be better).

Stock-and-flow diagrams are infrequently used because they depend on learners being experienced with system dynamics notation. They are generally used only in system dynamics curricula, where one of the goals is learning system dynamics methodologies. They would be useful when the learning environment's goals include validation of a model. Stock-and-flow diagrams show much more information than causal-loop diagrams, although still less detail than equations. They can also be combined with colorization, animation, and auditory techniques.

Structural equations, which may be combined with diagrams, show a great deal of detail, but in a way which may by detrimental for novice learners. Features of a dynamic model, such as loop dominance or rising versus falling stocks, are not easy to see in equations alone. But when the learner needs to see the way in which a particular variable changes based on other variables, equations are excellent. Equations can and probably should be combined with other techniques. For example, clicking on an equation might highlight icons in a corresponding diagram, or may initiate a auditory (voice-over) description of the equation and its role in the model. Structural equations are primarily for advanced or mathematically sophisticated learners and for circumstances where a very high degree of transparency and model detail is needed.

Tutorials are interactive lessons about a model that precede or are requested during use of a simulation or game (Goodyear, 1992). A tutorial may use text, voice, diagrams, or a combination. A good tutorial will be *interactive*, that is, present questions or other learner activities that practice and assess understanding of the model. The level of detail in tutorials can vary widely, and it can be quite low, so tutorials are more useful with novice learners and where a moderate or low level of transparency is desired.

Video techniques may be very useful for making models more transparent. Video techniques may be combined with many other techniques, such as tutorials or causal-loop diagrams. Examples include a teacher describing a model or an expert running and explaining a game. Video techniques may be very beneficial for novice learners, poorly motivated learners, and where low to moderate transparency is desired. For advanced learners or when greater transparency is desired, video can be combined with causal-loop diagrams or structural equations. If text captions and audio are included, video is particularly flexible for learners with disabilities. But based on the current system dynamics literature, video techniques have been little used for providing model transparency. This is probably because good video is difficult and expensive to produce, and requires high bandwidth for the increasingly popular web-based delivery.

As has been alluded to several times, these different techniques may be combined. Of particular value is the combination of visual techniques with voice narration. For example, a high level of transparency with maximal clarity might be achieved by combining either a causal-loop diagram or a stock-and-flow diagram with a narrator who describes the diagram and, as the model runs, who highlights characteristics such as loop dominance with colorization. The advantage of combining visual and auditory messages is well supported in the learning literature (Mayer, 2001; Clark & Paivio, 1991; Paivio, 1979). Paivio's *dual coding theory* and Mayer's *multimedia principle* both suggest that combining aural-verbal explanations (speech) with pictorial information (e.g., causal-loop diagrams) is a very effective instructional strategy.

Conclusion

Model transparency is clearly valuable in some learning environments for some purposes. But just as clearly, there are purposes and environments where *less* transparency is valuable. When the goal is to learn a *particular* model, greater transparency is probably indicated. When the goal is a more general one, less transparency may be better. In many system-dynamics-based learning environments, even when a particular model is being used, the real learning goal is not understanding the details of that *particular* model, but rather, is *learning to think about models.* For that purpose, intermediate levels of transparency might be appropriate.

It is important to remember that models are usually not "correct" or "true". Models are simplifications or reality, and often just theories. We should be wary that making a model very transparent will imply (incorrectly) to students that the model is well validated and accurate as it currently appears. That is often not the case. The less certain we are of a model's validity, the more opacity is suggested.

Lastly, we should be pleased that system dynamics is being applied to an ever-increasing number of educational purposes. For example, system dynamic methods and software are being used to design and implement simulations for scientific discovery learning or constructivist simulations in many academic areas (Feurzeig & Roberts, 1999; Harper et al., 2000; Jackson et al., 1994; Mandinach & Cline, 1994; Vavik, 1995; White, 1993; Zaraza et al., 1998). Such simulations will not always benefit from high levels of transparency. As system dynamics becomes used by more people in a widening variety of endeavors, we may need to loosen up on some of our cherished notions. The notion of high transparency may be good for traditional applications of system dynamics, but less useful for many new applications.

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