Cognitive Strategies in Dynamic Modeling: Case Studies of Opportunities Taken and Missed

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INTRODUCTION

New technologies offer new opportunities for engaging students in performances of higher-level thinking [Perkins 1985; Salomon, Perkins & Globerson 1991]. The increasing presence of sophisticated computers in classrooms, their expanding computational power, and advances in software interface design [Jackson, Stratford, Krajcik, & Soloway in press] bring opportunities closer to every student, and make it possible for them to engage in more sophisticated and technology-intensive activities such as dynamic modeling. Computer-based dynamic modeling has long been recognized as a scientific activity that promotes deep system analysis, careful cause-and-effect reasoning, and synthesis, along with articulating explanations about phenomena and testing and debugging. With the development of dynamic modeling environments for learners, we're investigating the extent to which students who construct dynamic models take advantage of those opportunities for cognitive engagement. Technology can play a supportive role in helping learners accomplish unfamiliar or cognitively difficult tasks [Guzdial 1995; Jackson et al. in press]. In this paper we present two case studies of pairs of students who, while creating models of their own design, engaged in a range of cognitive activities. The cases we present represent students in the middle range of abilities and performance: they did not struggle as they created their model, nor was what they produced exemplary.

Opportunities For Cognitive Performance Afforded By Dynamic Modeling

A review of literature on creating scientific models [Forrester 1968; Miller et al. 1993; Stratford 1996] suggests that there are many cognitive strategies in which a person may engage while creating a dynamic model of a system: analyzing it and identifying main components; reasoning about significant causal relationships; synthesizing components and relationships into a coherent model; testing and debugging the model; and verbalizing explanations. We'll refer to these various strategies as Cognitive Strategies for Modeling. Additionally, dynamic models may be viewed as "artifacts" because they are "critiquable, sharable externalizations of knowledge" [Guzdial et al. 1992]; they may demonstrate connections the modeler has made between concepts and may reveal what he or she understands about the subject matter of interest [Wisnudel et al. in press; Lehrer 1993]. Analysis of a model's structure, content, and behavior may reveal evidence for such understandings.

Modeling Process: Analyzing, Relational Reasoning, Synthesizing, Testing and Debugging, and Explaining

Analyzing is separating something whole into its constituent parts, and carefully examining those parts. Analysis is important in dynamic modeling because component parts and meaningful relationships between those parts are the building blocks from which a dynamic model is constructed. Analyzing a system may be carried out at a shallow or a deep level and with varying degrees of accuracy, depending upon the goals, knowledge, and skills of the modeler. As s/he creates a model, the modeler draws upon knowledge of and experience with other phenomena, or upon relevant science content knowledge.

Relational reasoning involves describing and defining relationships between parts of a system and drawing inferences and conclusions about the causal nature of those relationships. In causal reasoning, the modeler looks for a causal agent that causes changes in another part (or other parts) of the system, and then creates a mathematical representation in the model to mimic those changes. Causal reasoning is also applied when making predictions about the effects of changes to a system or about how a model should behave when it is run. Reasoning may also be invoked in judging or comparing the accuracy of a model's output in relation to actual data or to the real world.

Synthesizing a model refers to combining parts together to make a coherent whole. After analyzing a system into parts and selecting appropriate relationships between parts, the modeler synthesizes them into a coherent whole, literally "re-presenting" the phenomena inside the computer. The interrelationships between concepts, as formulated by the modeler into a model, will likely reflect many aspects of his or her understanding of the phenomenon, as may the behavior exhibited by the model when it is run (inasmuch as such behavior was intentionally designed into the model).

Testing and debugging enables one to ascertain whether a model is working as expected. Testing may focus on a single relationship to examine its operation (or to gain a better understanding of how it works), or on running an entire model with multiple inputs and outputs in order to observe its overall behavior under varying circumstances. The modeler debugs the model when, as it is tested, it doesn't behave as planned or expected. S/he may recognize that something is wrong, articulate the problem, and suggest and try some possible solutions. Debugging may also lead to rethinking one's reasoning about how the model was constructed.

Explanations are oral or written verbalizations of one's understanding of such things as the system's decomposition into parts, the mechanisms underlying a causal relation, or the reasoning for creating a model with certain behavior. Explanations may be simple statements of fact or definitions, reasons why something happens as it does, or explications of how some causal mechanism works. They may be incorporated into dynamic models through text fields, or may be embedded within the choice of terminology and definition of relationships. Explanations may also be expressed orally within the context of creating a model.

Modeling Product: Structure, Content, and Behavior

Dynamic models created with newer graphic-based modeling environments contain an observable configuration, or structure, of elements (such as stocks, flows or converters in the case of STELLA, or objects, factors, and relationships in the case of Model-It). A model's structure may correspond with the modeler's understanding of the phenomenon s/he is attempting to model. For example, if the modeler understands parts of a phenomenon to respond in a "chain reaction" fashion (that is, that an event can trigger a sequence of causal actions and reactions), then the modeler is likely to create a model of that phenomenon with a structure that visually resembles a chain or a line. Additionally, the model may or may not have a coherent structure in which all elements are unified into a model, and that structure may indicate how well the person who created it understands the phenomenon.

Because a model purports to represent some reality (some physical phenomenon, perhaps), it should contain representations of scientific content related to that phenomenon. If a scientist were to create such a model, s/he might incorporate scientific content with a great deal of precision, completeness, and accuracy. On the other hand, if a student created a model of the same phenomenon, s/he might include content with less precision, completeness, and accuracy. The difference between the two is in how deeply and broadly each understands the phenomenon. Thus, dynamic models may contain conceptual representations of the modeler's understanding of a phenomenon.

Dynamic models are designed to be run, that is, to take some values as input, to process, and to produce output. The input of a dynamic model consists of some starting conditions (or, in the case of interactive modeling software like Model-It, conditions that may be modified while the model runs). Processing is accomplished by a "simulation engine" that operates on the inputs according to carefully defined algorithms. Output is displayed as animations, graphs, or other visual displays. The output of a dynamic model, by its very nature, forms a pattern of behavior that can be observed, described, and analyzed. The goal, then, of creating a dynamic model is that its behavior mimic, in some carefully circumscribed way, the behavior of the phenomenon it is intended to represent. If we assume that the behavior observed when a model is run is the behavior the modeler intended it to have, then it is reasonable to infer that the model's behavior reflects the modeler's understanding of the phenomenon's behavior.

It is evident from the above discussion that opportunities for thinking exist in dynamic modeling. The question, therefore, is not *if* opportunities exist, but *whether students take advantage* of those opportunities to demonstrate and develop understanding [Perkins 1985].

OUR STUDY

For this paper, we draw upon data from a study of technology-enhanced project-based science in a ninth-grade science classroom located in a public, alternative school enrolling students with a range of racial, academic, and socioeconomic characteristics (though the majority of students are white middle- to upper middle-class). The science curriculum, called Foundations of Science [Huebel-Drake, Finkel, Stern & Mouradian 1995] combines modern data collection and processing technologies (e.g., portable computers and visualization software) with long-term authentic inquiry projects (in this case, local stream water quality monitoring). One component of this study has been to design, develop, and test dynamic modeling software, which has been dubbed "Model-It." Prior to their experience with Model-It, these students were engaged in a multi-month ecological investigation of a local stream, collecting, compiling, and reporting biological, physical, and chemical assessments. Their investigation involved considerable computer use, using them to organize data and to write and present their reports. Therefore participants entered this study with considerable prior knowledge of both stream ecosystems and computer technology.

In order to help the reader better understand how dynamic models are created with Model-It, we present a very brief description. To create a model of some phenomenon with Model-It, the user selects or creates *Objects* related to the phenomenon (for example, a golf course or an insect population), then defines quantifiable *Factors* of those objects (for example, the measured level of dissolved oxygen in a stream or the size of a golf course). Related factors are connected by *Relationships*, created using qualitative rather than formulaic representations. For example, a direct causal relationship represented mathematically by the function $y = x$ may be expressed qualitatively in Model-It with the phrase "as x increases, y increases by about the same." Verbal representations are visually linked with graphical representations. The model as a whole may be viewed with an abstract representation (similar to a concept map) called a *Factor Map*. Finally, the software provides graphs, meters, and sliders for interactively *Testing* the model. Space does not permit a complete description of the program's operation, but for a more complete description the reader may consult Jackson, Stratford, Krajcik and Soloway [in press].

After spending 6 days learning how to create models with Model-It (assisted by a written guide), students built stream ecosystem models based on several suggested ecological scenarios. They worked in pairs for 2 to 3 one-hour class periods, each pair sharing a computer and creating one model. Eight pairs (out of approximately 50) were selected for a focus group. As the focus group students worked on their models, the computer screen output, along with their conversations, was videotaped. The focus group students also completed a separate concept map on the topic of "the water in Traver Creek" prior to their modeling sessions in order to provide an indication of prior conceptual knowledge of stream ecosystems.

To analyze the videotaped data, we divided the modeling sessions into brief (two to fifteen minute) episodes based upon discrete activities (for instance, students creating a relationship would be one episode, while testing to see if the relationship worked would be another). Then we described what happened in each episode, categorizing each episode by event and task (e.g., "creating relationships" or "running the model"). Then we analyzed each *episode* description for evidence that students were engaging in Cognitive Strategies for Modeling, attempting to capture characteristics and quality of their engagement in the form of a high-level analytical narrative. Finally, using the narratives of Cognitive Strategies for all episodes, we looked for patterns in students' modeling process, illustrating those patterns by selecting examples from the descriptions, transcripts, and analytical narratives, and articulating statements capturing the essence of the patterns we observed. The goal of our final analysis write-up was to *compose* a case story about the strategies in which each group engaged while creating their model, in order to capture both the characteristics and qualities of students' modeling process.

To analyze the model data, we evaluated each model's structure, content, and behavior. Structure was evaluated by a model's *form* (e.g., "star" or "linear") and *coherency* ("unified," "partially fragmented," or "fragmented"). Content was evaluated for factors, relationships, and written explanations in the model. Factors were assessed according to the accuracy (according to generally accepted scientific knowledge) of their descriptions and ranges, and according to breadth (how well the selected factors "covered" the scenario). Relationships were assessed according to their accuracy of definition. Explanations were assessed as to their accuracy, depth (e.g., "descriptive," "correlational," or "causal"), and integration (inclusion of relevant examples or scientific content). Behavior was evaluated in two areas: behavior over time ("constant," "straightforward complex," or "sophisticated complex") and fidelity (how closely the behavior of the model matched the expected behavior of the scenario or phenomenon).

For this paper, we selected two out of the eight focus group cases for discussion. Both cases represent moderate levels of engagement in thinking strategies; that is, in both cases, students engaged in some but not all Cognitive Strategies for Modeling, and they produced acceptable but not necessarily outstanding models. For each, we provide a brief profile of background information, such as the topic they chose for their model, a rough assessment of prior knowledge, how well they appeared to work together or relate to technology, and how many guide sections they completed. Then we discuss results related to their modeling process and product. Finally, for each case, we present an interpretation in which highlights of their modeling process are related to their product.

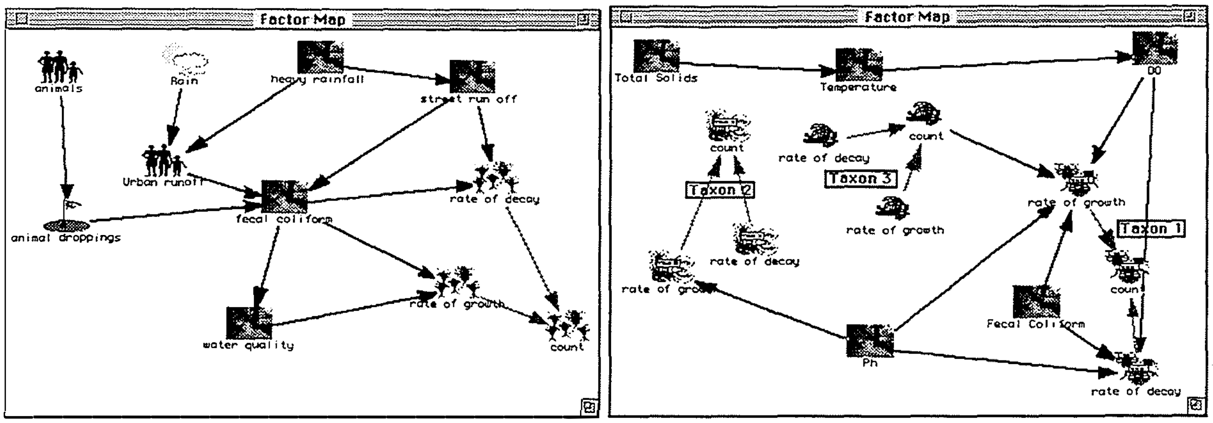
CASE 1–CORY AND DAN

Profile

Cory and Dan chose to create a model showing the impact, on a stream ecosystem, of urban runoff (such as sewage overflow or urban street runoff) containing human and animal waste [see Fig. 1 for a "Factor Map" of their model]. In their self-paced introductory work, they had completed all seven (through predator-prey models) before working on their final model. They had comparable, moderate prior knowledge of stream ecosystems, as evidenced in their fairly well-developed and interconnected concept maps. They seemed to work well together during their two modeling sessions and seemed comfortable using the computer technology.

Process

Cory and Dan's modeling process was marked by frequent planning and thorough analysis of potential factors and key relationships, but they seemed to engage in somewhat shallow reasoning, little causal explanation, and minimal testing. They analyzed their model scenario in depth by generating many ideas for factors, but most of their reasoning about how those factors were related was either shallow or nonexistent. When present, their reasoning was more correlational than causal. However, they attempted to carefully reason out several key relationships in their model, specifically, the relationships between "runoff," "animal feces," "fecal coliform," and "water quality." When they viewed the Factor Map, it seemed to catalyze their analysis and synthesis activities by helping them think of additional factors to include and by helping them focus on their overall modeling goal. Several times during their two modeling sessions they stopped to consider their course of action. On the other hand, they engaged in very little verbal explaining during their conversations, included no written explanations in their model during the two modeling sessions that were recorded. Their few explanations seemed to be based more upon correlational reasoning, with only a few instances in which they discussed causality between factors. They tested their model a few times, but engaged in very little conversation about what they were observing, neither about whether the model was behaving as they expected nor whether the model was behaving realistically. They made no attempt to identify any problems with their model or to "debug" it.



Figures 1 & 2. Cory & Dan's model, left; Rachel and Sam's model, right (Factor Map representations).

Product

Cory and Dan's model was coherent and generally accurate, but a few aspects of its behavior were faulty. In their model [Figure 1], "animals," "heavy rainfall," and "rain" affect "fecal coliform," "street runoff" and "water quality," which in turn affect the "mayfly" population. The qualitative relationships between those factors was as expected according to the scenario they were attempting to model (e.g., higher levels of fecal coliform cause water quality to decrease, etc.). Their model's structure was somewhat like a "funnel," with inputs from "animals" and "rain" and "heavy rainfall" eventually affecting the single factor "fecal coliform," which in turn affected both "water quality" and the macroinvertebrate population (the grouping of three factors to the right, "count," "rate of growth," and "rate of decay." There were no descriptions for factors; consequently, factor accuracy could be assessed only on the names and ranges of factors. Some ranges (e.g., for fecal coliform) were accurate according to water quality definitions, and others (e.g. "animals") were defined with default ranges assigned by Model-It. Their relationships were qualitatively accurate. It should be noted here that during their two class periods of modeling, they did not type in any explanations into Model-It; however, their final model contained typed explanations, so they obviously typed those explanations in outside of class. Most of their written explanations were accurate but a few were questionable or wrong; some explanations were deeper than others and contained expressions of causality.

Their model behaved in a straightforward complex manner: raising the "animals" factor made "animal droppings" go up, which made "fecal coliform" rise, which made quality go down; more "rain" led to increased "urban runoff," an increase in "fecal coliform," and a decrease in quality. The mayfly population, however, did not appear to work properly–it always rose to its maximum and stayed there, regardless of the how the independent variables ("animals" or "rain") were set. The overall effect of the model (changes in fecal coliform leading to eventual effects upon the benthic macroinvertebrate population) is questionable, because the presence of more fecal coliform may *correlate* with fewer benthics depending on other conditions, but fecal coliform bacteria by themselves don't necessarily *cause* an adverse effect upon benthics).

Interpretation

Cory and Dan's frequent planning and thorough analysis helped them to create a model with fairly rich and generally accurate content. Their focus on several key relationships helped them organize their model into a coherent structure. However, their overall lack of discussion of causality in their relationships, perhaps combined with a faulty conception of how macroinvertebrates are affected by fecal coliform, may have led to the flaw in the overall synthesis of their model. Also, the few times they tested their model were probably insufficient for them to understand how their model behaved, which may account for the questionable mayfly population behavior.

CASE 2–RACHEL AND SAM

Profile

Rachel and Sam chose to create a model showing how benthic macroinvertebrate organisms in a stream can be indicators of water quality [see Figure 2]. They completed all seven sections of the guide. They were pretty well matched in terms of prior knowledge; both of their concept maps were accurate, each containing seventeen concepts and a moderate level of connectivity. They seemed to work together well, and generally attended to the modeling task. There were a few occasions, however, in which they had difficulty with the operation of the computer or Model-It and became frustrated when the computer didn't do what they thought it should.

Process

Rachel and Sam's modeling process was characterized by analyzing with the help of a reference source, both causal and non-causal reasoning and explaining, using the Factor Map as an aid to synthesizing their model, encountering procedural problems they couldn't solve, and engaging in testing with which they were not satisfied. As they analyzed their scenario, they frequently referred to their water quality text. They used the text to look for potential factors and to refresh their memory about how potential factors were related to other factors. Their modeling sessions were marked by both causal and non-causal reasoning and explanations. That is, some of the relationships they created were causal, and they discussed them appropriately, but other relationships they discussed were not causal, but they talked about them as if they were causal. For example, they discussed the relationship between "temperature" and macroinvertebrate populations by saying that temperature affected "water quality" and quality then affected macroinvertebrates. Although there may be a causal relationship between temperature and macroinvertebrates, the one they were discussing was correlational at best. They used the Factor Map as an aid to synthesizing their model: it helped them see what they had so far and helped them find unfinished portions. On several occasions in their modeling sessions, they encountered procedural problems that they were unable to solve. For example, on several occasions they attempted to create relationships to factors of a population, but in each case experienced some difficulty figuring out how to do it. Finally, they seemed to be unsatisfied with attempts to test their model. Each time they tried to test it, the populations whose behavior they were trying to test did not seem to behave in a realistic way as they expected, and they never did identify the bugs they thought were in their model.

Product

The model they created to show how water quality factors affected macroinvertebrates [Figure 2] was structured so that "total solids," "pH," and "fecal coliform" affected two benthic populations, Taxon 1 and Taxon 3 (the third benthic population, Taxon 2, also acted as an independent variable, directly affecting the Taxon 1 rate of growth). Factors were accurately described and factor ranges were either accurate according to water quality definitions or else were defined using Model-It's default. Most relationships and their explanations were accurate, although several were questionable, such as the connection between total solids and temperature (they explained that more total solids would increase heat absorption, thus increasing the temperature of the water) or the connection between Taxon 2 and Taxon 1 mentioned above. Some of their explanations expressed causality but others did not. Their model exhibited straightforward complex behavior with moderate fidelity to reality. The Taxon 1 benthic population responded as expected to changes in total solids, pH, and fecal coliform, but the Taxon 3 population did not respond to any changes in the independent variables. Although Taxon 3 is the most pollution tolerant of all three taxa, at high levels of pollution they should be adversely affected; their model doesn't reflect that behavior.

Interpretation

Rachel and Sam's process of searching an information source during their analysis helped them create a model with mostly accurate factors and relationships. Their reference to the Factor Map helped them synthesize a unified model. However, their somewhat mixed causal and correlational reasoning may have led to the creation of several questionably causal relationships. The difficulties they encountered with testing and with connecting factors with populations may have resulted in a model with behavior that was only partially realistic.

DISCUSSION

The two cases presented here illustrate how, when using Model-It to create dynamic models, students take advantage of some opportunities for thinking but don't take advantage of others as much as we'd like them to. Both cases show them taking opportunities for analyzing an ecosystem scenario by thinking of relevant factors, using both prior knowledge and classroom reference sources to generate ideas. They also took the opportunity to synthesize a model, as evidenced by the relatively coherent models they created, and as seen in the ways they made use of the visual representation of their model in the Factor Map. Opportunities for reasoning and explanation were inconsistently taken: in one case, the students expended effort reasoning about a few key relationships, but did not explain the causal mechanisms upon which many of their relationships were based; in the other case, the students mixed causal and correlational reasoning, consequently producing a model with several questionable relationships. Finally, neither group of students effectively tested their model, with one group engaging in superficial testing, and the other encountering difficulties they didn't understand and apparently giving up.

The results should not be surprising. We should not expect students to take part in the full range of Cognitive Strategies for Modeling in their first attempts to create models of a complex system. Based on the evidence presented, students took part in some of the Cognitive Strategies for Modeling that we would hope they could perform; moreover, they created reasonable models. However, to promote students' participation in the full range of Cognitive Strategies for Modeling, enabling them to create models with coherent structure, rich content, and realistic behavior, we still need to think of more ways to encourage and support their efforts. Several possibilities are suggested here, in two areas: software support and instructional support. First, in order to support articulating causal explanations in the software, we suggest that the relationship-construction tools of Model-It should not be blank, but should include text fields "seeded" with a causal phrase, for example, "Golf course size affects stream fertilizer runoff because ___." This would focus students' attempts to type explanations upon the causal mechanism. Second, in order to support testing and debugging in the software, we suggest that the software monitor students' actions with the software and when some number of relationships have been created, to prompt the user to test the model. In addition, we also suggest that students be prompted to reflect upon the results of their testing and to record predictions, observations, and conclusions. Third, to support causal reasoning, teachers should discuss the differences between causes and correlations and provide opportunities for students to identify and articulate statements of both kinds. Finally, to support more accurate and coherent models with higher fidelity behavior, we suggest that models should be critiqued and revised by other student groups, by teachers, or by experts in the field. This will allow additional opportunities to engage in a cycle of development and revision of not only the model itself, but of students' understanding.

REFERENCES

Forrester, J. W. (1968). Principles of systems. Cambridge, MA: Wright-Allen Press.

Guzdial, M., Soloway, E., Blumenfeld, P., Hohmann, L., Ewing, K., Tabak, I., Brade, K. (1992). *The future of computer-assisted design: technological support for kids building artifacts.* In D. Balestri, S. Ehrmann, & D. Ferguson (Eds.), Learning to Design, Designing to Learn. Washington: Taylor & Francis.

Guzdial, M. (1995). Software-realized scaffolding to facilitate programming for science learning. Interactive Learning Environments, 4 (1), 1-44.

Huebel-Drake, M., Finkel, E., Stern, E., & Mouradian, M. (1995). Planning a course for success. The Science Teacher, 62 (7), 18-21.

Jackson, S., Stratford, S. J., Krajcik, J. & Soloway, E. (in press). Making dynamic modeling accessible to pre-college science students. Interactive Learning Environments.

Lehrer, R. (1993). *Authors of knowledge: patterns of hypermedia design.* In Computers as Cognitive Tools. In S. D. Lajoie, S. (Eds.) Hillsdale, NJ: Lawrence Erlbaum Associates, 197-228.

Miller, R., Ogborn, J., Briggs, J., Brough, D., Bliss, J., Boohan, R., Brosnan, T., Mellar, H., & Sakonidis, B. (1993). Educational tools for computational modelling. Computers in Education, 21 (3), 205-261.

Mitchell, M. K. & Stapp, W. B. (1994). Field manual for water quality monitoring: an environmental education program for schools. (8th ed.). Dexter, MI: Thomson-Shore Printers.

Perkins, D. N. (1985). The fingertip effect: How information-processing technology shapes thinking. Educational Researcher, August/September, 11-17.

Salomon, G., Perkins, D., & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. Educational Researcher, 20 (3), 2-9.

Stratford, S. J. (1996). *Opportunities for thinking: constructing models in precollege science classrooms.* Paper presented at the Annual Meeting of the American Educational Research Association. New York, New York, April, 1996.

Wisnudel, M., Stratford, S., Krajcik, J., Soloway, E. (in press). *Using technology to support students' artifact construction in science.* To appear in Linn, M.C. (Ed.) Int'l Handbook of Science Education. Netherlands: Kluwer.

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