Artificial Intelligence in Education
C.-K. Looi et al. (Eds.)
IOS Press, 2005

Teaching about Dynamic Processes A Teachable Agents Approach

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Abstract. This paper discusses the extensions that we have made to Betty's Brain teachable agent system to help students learn about dynamic processes in a river ecosystem. Students first learn about dynamic behavior in a simulation environment, and then teach Betty by introducing cycles into the concept map representation. Betty's qualitative reasoning mechanisms have been extended so that she can reason about cycles and determine how entities change over time. Preliminary experiments were conducted to study and analyze the usefulness of the simulation. Analysis of the students' protocols was very revealing, and the lessons learnt have led to redesigned simulation interfaces. A new study with the system will be conducted in a fifth grade science classroom in May, 2005.

1. Introduction

Modern society is engulfed by technology artifacts that impact every aspect of daily life. This makes learning and problem solving with advanced math and science concepts important components of the K-12 curriculum. Many of the teaching and testing methods in present day school systems focus on memorization and not on true understanding of domain material [1]. Lack of systematic efforts to demonstrate the students' problem solving skills hamper the students' abilities to retain what they have learned, and to develop the competencies required for advanced science and technology training in the future. A solution proposed by researchers is to introduce constructivist and exploratory learning methods to help students take control of their own learning and overcome the problems of inert learning and learning without understanding [1].

The cognitive science and education literature has shown that teaching others is a powerful way to learn [23]. Preparing to teach others helps one gain a deeper understanding of the subject matter. While teaching, feedback from students provides the teacher with an opportunity to reflect on his or her own understanding of the material [4]. We have adopted the *learning by teaching* paradigm to develop an intelligent learning environment called Betty's Brain, where students teach Betty, a software agent, using a concept map representation [5]. Experiments conducted with Betty's Brain in fifth grade science classrooms demonstrated that the system is successful in helping students learn about river ecosystem entities and their relationships [6]. Students showed improved motivation and put in extra effort to understand the domain material. Transfer tests showed that they were better prepared for "future learning" [7].

In the current version of the system, Betty's representation and reasoning mechanisms are geared towards teaching and learning about *interdependence* in river ecosystems. However, analysis of student answers to post-test questions on *balance* (*equilibrium*) made it clear that students did not quite grasp this concept and how it applied to river ecosystems.

We realized that to understand balance, students had to be introduced to the dynamic behavior of river ecosystems. This brought up two challenges. First, how do we extend students' understanding of interdependence to the notion of balance, and second, how should we extend the representation and reasoning mechanisms in Betty's Brain to help middle school students learn and understand about the behavior of dynamic processes.

Analyzing dynamic systems behavior can be very challenging for middle school students who do not have the relevant mathematical background or maturity. To overcome this, we introduced the notion of cycles in the concept map representation to model changes that happen over time. To scaffold the process of learning about temporal effects, we designed a simulation that provides a virtual window into a river ecosystem in an engaging and easy to grasp manner. This brings up another challenge, i.e., how do we get students to transfer their understanding of the dynamics observed in the simulation to the concept map representation, where changes over time are captured as cyclic structures.

This paper discusses the extensions made to the concept map representation and the reasoning mechanisms that allow Betty to reason with time. A protocol analysis study with high school students pointed out a number of features that we needed to add to the simulation interfaces to help students understand dynamic behaviors. The redesigned simulation interfaces will be used for a study in a middle school science classroom in May 2005.

2. Betty's Brain: Implementation of the Learning by Teaching Paradigm

Betty's Brain is based on the learning by teaching paradigm. Students explicitly teach and receive feedback about how well they have taught Betty. Betty uses a combination of text, speech, and animation to communicate with her student teachers. The teaching process is implemented through three primary modes of interaction between the student and Betty: teach, quiz, query. Fig. 1 illustrates the Betty's Brain system interface. In the teach mode, students teach Betty by constructing a concept map using an intuitive graphical point and click interface. In the query mode, students use a template to generate questions about the concepts they have taught her. Betty uses a qualitative reasoning mechanism to reason with the concept map, and, when asked, she provides a detailed explanation of her answers [5]. In the quiz phase, students can observe how Betty performs on a pre-scripted set of questions. This feedback helps the students estimate how well they have taught Betty, which in turn helps them reflect on how well they have learnt the information themselves. Details of the system architecture and its implementation are discussed elsewhere [589].

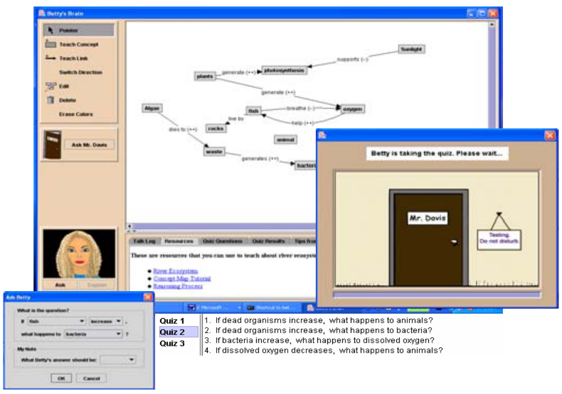

Figure 1: Betty's Brain interfaces

The system, implemented as a multi-agent architecture, includes a number of scaffolds to help fifth grade students in science classrooms. These include extensive searchable online resources on river ecosystems and a mentor agent, Mr. Davis, who not only provides feedback to Betty and the student but also provides advice, when asked, on how to be better learners and better teachers. Experimental studies in fifth grade classrooms have demonstrated the success of Betty's Brain in students' preparation for future learning, in general, and learning about river ecosystems, in particular [56].

3. Extending Betty's Brain: Introducing the temporal reasoning framework

One of our primary goals is to help students extend their understanding of interdependence among entities in an ecosystem to the dynamic nature of the interactions between these entities, so that they may reason about and solve problems in real world processes. Middle school students lack the knowledge and maturity to learn about mathematical modeling and analysis approaches for dynamic systems using differential equations. As an alternative, we have to develop intuitive approaches based on simplified, qualitative representations [10, 11] that capture the notion of change over time, hide complex details, but are still accurate enough to replicate the behavior of a real world ecosystem. Even experts use qualitative representations to develop quick, coarse-grained solutions to problems, and explanations for how these solutions are derived [14]. Researchers have used this approach to help students develop high level reasoning skills that are linked to mathematical methods [11].

In this work, we build on the existing qualitative reasoning mechanisms in Betty's Brain to incorporate temporal representations and reasoning. To avoid confusion and cognitive overload, these new additions have to be seamless extensions of the previous representation and reasoning mechanisms. Also, to accommodate our novice student learners, it is important to provide them with scaffolds to aid their understanding of dynamic system behavior. In the learning by teaching framework, the student teachers are given opportunities to learn and understand the material to be taught before they proceed to teach Betty. To help students in their preparations to teach, we have designed and implemented a simulation of a river ecosystem. In the rest of this section, we describe the simulation system, and the extensions to Betty's qualitative reasoning mechanism.

3. 1. The Simulation

In constructivist approaches to learning, students are encouraged to direct and structure their own learning activities to pursue their knowledge building goals [12]. To facilitate this approach to learning, we provide the students with an exploratory simulation environment, where they are exposed to a number of situations that makes them aware of the dynamic phenomena that occur in river ecosystems. The simulation includes a variety of visual tools that the students can use to observe how entities change over time, and how these changes interact to produce cycles of behavior in the ecosystem.

3.1.1 The mathematical model and simulator

The interacting entities in a river ecosystem are typically modeled as differential equation or discrete time state space models. Our river ecosystem simulation is based on a discrete-time model that takes the form: $x_{t+1} = f(x_t, u_t)$, where x_{t+1}, the state vector at time step $t+1$ is defined as a function of the state of the system, x_t, and the input to the system, u_t at time step *t*. We create a one-to-one mapping between the state variables in the simulation, and the entities in the river ecosystem expert concept map that are created by the fifth grade science teachers. This concept map includes the following entities: fish, algae, plants, macro invertebrates, bacteria, oxygen, waste, dead organisms, and nutrients. The quantity of each of these entities is represented by a state variable, and a typical state equation takes on the following form:

$$O_{2t+1} = O_{2t} + 0.001125.P_t - 0.006.F_t - 0.001.M_t + 0.00075A_t - 0.0004.B_t$$

This linear equation describes the change in the amount of dissolved oxygen, O_2, from one time step to the next for the ecosystem in balance. $O_{2t}, P_t, F_t, M_t, A_t,$ and B_t represent the quantity of dissolved oxygen, plants, fish, macroinvertebrates, algae, and bacteria, respectively, in appropriate units at time step, *t*. The coefficients in the equation represent the strength of interactions between pairs of entities. For example, the coefficient for F_t is greater than the coefficient for M_t because fish consume more oxygen than macro invertebrates. Producers of oxygen, plants and algae, have positive coefficients and consumers, fish, macroinvertebrates, and bacteria, have negative coefficients in the above equation.

The state equations would have been much more complex with steep nonlinearities, if we had included phenomena, where the river did not remain in balance. Instead, we employ a hybrid modeling approach, and switch the equations when the entities exceed predefined critical values. For example, if the amounts of dissolved oxygen and plants fall below a certain value, they have a strong negative effect on the quantity of fish in the river. This phenomenon is captured by the following equation:

$$\text{If } O2_t < 3 \text{ (ppm) and } P_t < 3500 \text{ (micromg/L)}$$

$$F_{t+1} = F_t - ((6 - O2_t)/300).F_t - ((4000 - P_t)/50000).F_t$$

Therefore, our state equation-based simulation model captures the behavior of a river ecosystem under different operating conditions that include the behavior of the ecosystem in balance and out of balance.

The simulation model was implemented using AgentSheets [13], which is a software tool designed to facilitate the creation of interactive simulations using a multi agent framework. This tool was chosen primarily because it provides an easy way to construct appealing visual interfaces. Its user friendly drag and drop interface made it easy to implement the simulation model. Each entity was modeled as an agent with the appropriate set of equations describing its behavior at every time step.

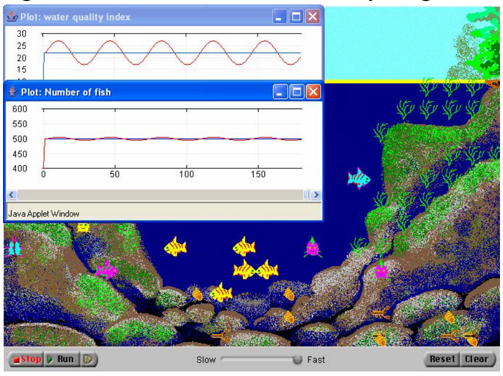

Figure 2: The simulation interface

3.1.2 The visual interface

Fig. 2 illustrates the visual interface of the simulation system. It has two components. The first uses an animation to provide a virtual window into the ecosystem. Its purpose is to give the student an easy to understand global view of the state of the system. The second component uses graphs to give a more precise look at the amount of the different entities and how these amounts change with time. The student can use these graphs to not only determine the amounts, but also study patterns of change. Further, since the cyclic behavior of the variables was clearly visible in these plots, we believed that students could use these graphs to learn about cycle times, and teach Betty this information in the concept map representation.

3.1.3 Ranger Joe

Ranger Joe plays the role of the mentor in the simulation environment. He provides help on a variety of topics that range from textual descriptions of the simulation scenarios, to telling students how to run the simulation, and how to read the graphs. When asked, he makes students aware of the features available in the simulation environment, and how students may use them to learn more about dynamic changes in the river. The current version of Ranger Joe provides responses in text form only.

3.2. Extending Betty's reasoning mechanisms to incorporate temporal reasoning

As discussed earlier, we have extended the concept map representation in Betty's Brain to include cyclic structures. Any path (chain of events) that begins on a concept and comes back to the same concept can be called a cycle. For example, the concepts macroinvertebrates, fish, and dissolved oxygen form a cycle in the concept map illustrated in Fig. 3. Unlike the previous version of Betty's Brain, where the reasoning process only occurred along the paths from the source to the destination concept (identified in the query), e.g., "*If* *fish increase what happens to bacteria*?", the new system also takes into account the changes that occur along feedback paths from the destination to the source concept. For example, a change in the amount of bacteria above may cause a change in the amount of fish along the feedback path, which would further cause a change in bacteria along the forward path and so on. This creates a cycle of change and the time it takes to complete an iteration of the cycle is called the cycle time.

The query mechanism had to be extended so Betty could answer questions that involved change over time, e.g., "*If algae decrease a lot, what will happen to bacteria after one month*?" Last, Betty's reasoning and explanation mechanisms were extended. Each of these is described below.

3.2.1. Concept Map Building and Query Interfaces

We extended the concept map interface to allow students to teach Betty about dynamic processes by constructing a concept map with cycles (see Fig. 3). To help Betty identify a cycle in the concept map, students click on the "Teach Cycle" button, which brings up a pop up window with the same name. Students identify the cycle, using any one of the nodes as the starting point, e.g., *crowded algae* in cycle 2 (Fig. 3) then identify the other concepts in the cycle in sequence, e.g., *dead algae*, then *bacteria*, and then *nutrients*. Along with each cycle, the student also has to teach Betty the time (in days) it takes to complete an iteration of the cycle. Betty responds by identifying the cycle with a number. Fig. 3 shows the concept map after the student has built two cycles identified by Betty as cycles 1 and 2 with cycle times of 5 and 10 days, respectively.

Like before, students can query Betty. The original query templates were extended as shown in Fig. 3 to include a time component.

3.2.2. Temporal Reasoning Algorithm and Explanation Process

The extended temporal reasoning algorithm that Betty uses has four primary steps. In step 1, Betty identifies all the forward and feedback paths between the source and destination concepts in the query. For the query, "*If algae decrease a lot, what will happen to bacteria after one month*?" Betty identifies *algae* as the source concept and *bacteria* as the destination concept. A forward path is a path from the source to the destination concept (e.g., *algae* → *crowded algae* → *dead algae* → *bacteria*) and the feedback path traces back from

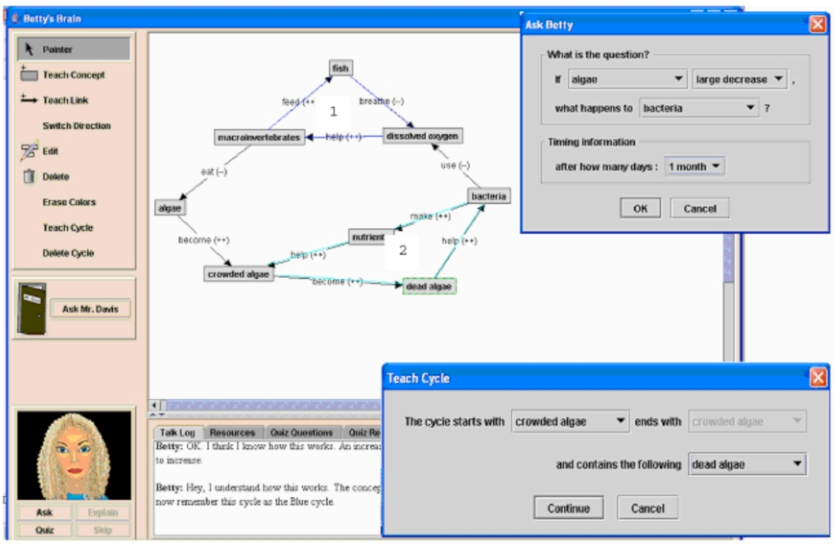

Figure 3: Betty's Brain: Temporal Reasoning Interface

(**top-right): temporal question template; (bottom-right): interface for teaching Betty about cy-**

the destination to the source concept (e.g., *bacteria* → *dissolved oxygen* → *macroinvertebrates* → *algae*). In step 2, using the original reasoning process [5], all the concepts on these paths are given an initial value. In step 3, Betty orders the cycles from slowest to fastest, and executes the propagation of the chain of events for each cycle. When a path includes more than one cycle, the faster cycle is run multiple times, and then its effects are integrated with the chain of events propagation in the slower cycle. This method incorporates the time-scale abstraction process developed by Kuipers [014]. This process is repeated for the feedback path, and the result gives the updated values for the source and destination concepts after one full cycle. In step 4, this process is repeated multiple times till the value of the destination concept has been derived for the time period stated in the query.

For example, when asked the query about algae and bacteria, Betty first identifies the forward and feedback paths shown earlier, and propagates the change of algae to the concepts on the forward path and then to the concepts on the feedback path using the original reasoning mechanism. She determines that *crowded algae*, *dead algae* and *bacteria* decrease a lot on the forward path, and *dissolved oxygen*, and *macroinverterbrates* increase a lot. In step 2, she identifies two cycles (cycles 1 and 2 in Fig. 3), one on the forward path, and the second on the feedback path. Since cycle 2 has the larger cycle time, she assigns the main cycle a period of 10 days. After that, she runs the reasoning process twice (10/5) for cycle 1 and determines that *macroinverterbrates* and *fish* increase a lot and *dissolved oxygen* decreases a lot. Cycle 2 is run once (10/10) to derive that *crowded algae*, *dead algae,* and *nutrients* decrease a lot. Betty then combines the effects of cycles 1 and 2 to determine the value for *algae* after 10 days (feedback effect), i.e., *algae* decrease a lot, and, as a result, *bacteria* decrease a lot (this completes one cycle, i.e., a 10 day period of behavior). Since the student wanted to know what happens to *bacteria* after one month, this process has to be repeated three times, and Betty arrives at the answer that *bacteria* decrease a lot.

To facilitate student's understanding of the temporal reasoning mechanisms, Betty uses a top-down explanation process, if asked to explain her answer. First, Betty explicates her final answer, and states how many full cycles she had to run to get this answer. Then Betty breaks down the rest of the explanation cycle by cycle, and then combines the results. Students can control what parts of the explanation and how much detail they want, by simply clicking on "Continue Explanation," "Repeat," and "Skip" buttons in left bottom of the interface.

4.0 Protocol Analysis Studies with the Temporal Betty

We conducted a preliminary protocol analysis study with 10 high school students. None of these students knew or remembered much about the river ecosystems unit they had covered in middle school. The overall goal for each student was to teach Betty about the dynamic processes in river ecosystems by first teaching her about general concepts of the ecosystem by drawing a concept map and then refining the map by identifying cycles and teaching her timing information. One of our goals was to see how they would use the simulation tool to derive information about the structure and time period of cycles. Each student worked with a research assistant (who conducted the study) on the Betty's Brain system for two one hour sessions. As students worked, the research assistants involved them in a dialog, in which they asked the students to interpret what they saw in the simulation, and how that information may be used to teach Betty using the concept map structure. All verbal interactions between the student and the researcher was taped, and later transcribed and analyzed. An overview of the results is presented next.

Overall, all students liked the simulation and felt that it was a good tool for learning about river ecosystems. Also, they thought that the river animation was engaging and served the purpose of holding the student's attention. The researchers asked specific questions that focused on students' understanding of graphs, cycles and cycle times. An example dialog that was quite revealing is presented below.

Researcher: So do you think the graphs were helpful in helping you think about the temporal cycles?

Student: They were critical because that's where I got my initial impression because ordinarily when someone gives you something to read, it's really a small amount of text and doesn't clarify much. So the graphs are the main source of information.

Also, some of the dialogues indicated that the graphs were put to good use in learning about cycle times. For example, a student, who was trying to find the cycle time involving fish and macro invertebrates said:

Researcher: Are you trying to assign the time period of the cycle?

Student: Yeah, see how the cycle kind of completes the whole graph in about 2 days.

A second example:

Researcher: What is hard about using the graphs?

Student: Well, I see the graph; I see the sine wave and the period of the sine wave, right here, right?

Researcher: Right.

Student: So I would think of that as completing the cycle.

Students also made some important suggestions about the graphs. Many of them mentioned that it would be better to have multiple quantities plotted on the same graph. Some of them said that it would be useful to have quantities plotted against each other rather than plotted against time so that relationships between such quantities could be observed directly. Others said that simply showing numbers of changing quantities over time would be useful too.

We also had some feedback about the resources and feedback that Ranger Joe provided. The students found the text resources to be useful but thought there was too much to read, so it would be a good idea to reorganize the text into sections and make it searchable. They also thought that Ranger Joe was passive, and that he should be an active participant in the learning process. Most students stressed the importance of being able to easily navigate between different graphs and see them side by side for easy comparisons.

These protocols provided valuable feedback on the effectiveness of the different features of the simulation. We realized some of the features would have to be modified, and extra features had to be implemented. These changes could not be implemented in AgentSheets. This motivated us to redesign and reimplement the simulation in a flexible programming environment like Java to facilitate the addition of new tools and easy integration of the simulation and Ranger Joe with the temporal Betty system.

5.0 The Redesigned Simulation System

Different representations enhance different aspects of thinking and problem solving skills. In the new simulation, we present the state of the river ecosystem using a number of different representations that are more relevant to their problem-solving tasks. In this version of the simulation, we provide the students with a new set of tools which exploits the use of representations as a critical tool of thought. We also hope that this will help students develop representational fluency, which is an important attribute to have while attempting to solve complex real world problems.

The tools for the presentation and analysis of the information in the graphs have been revamped. Students can now choose the graphs they want to view from a pull-down menu. They can choose between line graphs and bar graphs. The unit of time for the bar graph plots can be a day (unit of time in the simulation), or a week (typically the frequency with which experimental data is collected in rivers). A second feature introduced is a compare graph tool that allows the student to plot multiple quantities in the same graph to get a better idea of the interrelationships between the entities. The students can also view the simulation data in tabular form. A third tool will help students analyze the temporal change in the quantities in a more abstract qualitative way. Changing trends are depicted by upward facing arrows (increase in the quantity) and downward facing arrows (decrease in the quantity). This representation provides information that is closer to what students need to generate the concept map.

The text resources have been restructured and reorganized in a hypertext form. They contain a detailed description of how to use the different tools in the simulation and how to use and interpret graphs. A keyword search features helps students to easily find the specific information they are looking for. The mentor agent, Ranger Joe, plays a more active role in this new environment. He can address specific questions that the student might have, and gives feedback that is tailored to the students' current activities.

5.0 Discussion and Future Work

Our upcoming study with middle school students starting in May, 2005 will focus on evaluating the usefulness of the system (temporal Betty + the simulation) in teaching about dynamic processes in a river ecosystem. In particular, we want to find how easy it is for students to understand the notion of timing and cycles and also how well they can learn to translate timing information in the simulation into the concept map framework. Also, we want to study the various graph representations in terms of their general usefulness, their frequency of use, and their success in helping students learn about the dynamic nature of ecosystem processes.

Acknowledgements: This project is supported by NSF REC grant # 0231771.

References

1. Bransford, J.D., A.L. Brown, and R. R. Cocking (2001). How People Learn: Brain, Mind, Experience and School.
2. Palinscar, A. S. & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension -monitoring activities. Cognition and instruction, 1: 117-175.
3. Bargh, J. A., & Schul, Y. (1980). On the cognitive benefits of teaching. *Journal of Educational Psychology, 72*(5), 593-604
4. Webb, N. M. (1983). Predicting learning from student interaction: Defining the interaction variables. *Educational Psychologist*, 18, 33-41.
5. Biswas, G., D. Schwartz, K. Leelawong, N. Vye, and TAG-V (2005). "Learning by Teaching: A New Agent Paradigm for Educational Software," *Applied Artificial Intelligence*, special issue on Educational Agents, 19(3): 363-392.
6. Biswas, G., Leelawong, K., Belynne, K., et al. (2004). Incorporating Self Regulated Learning Techniques into Learning by Teaching Environments. *26th Annual Meeting of the Cognitive Science Society*, (Chicago, Illinois, 120-125.
7. Schwartz, D. L. and Martin, T. (2004). Inventing to prepare for learning: The hidden efficiency of original student production in statistics instruction. *Cognition & Instruction,* 22: 129-184.
8. Biswas, G., Leelawong, K., Belynne, K., et al. (2004). Developing Learning by Teaching Environments that support Self-Regulated Learning. in *The seventh International Conference on Intelligent Tutoring Systems*, Maceió, Brazil, 730-740.
9. Leelawong, K., K. Viswanath, J. Davis, G. Biswas, N. J. Vye, K. Belynne and J. B. Bransford (2003). Teachable Agents: Learning by Teaching Environments for Science Domains. *The Fifteenth Annual Conference on Innovative Applications of Artificial Intelligence*, Acapulco, Mexico, 109-116.
10. Bredeweg, B., Struss, P. (2003). Current Topics in Qualitative Reasoning (editorial introduction). *AI Magazine*, 24(4), 13-16.
11. Bredeweg, B., Forbus, K. (2003). Qualitative Modeling in Education. *AI Magazine*, 24(4). 35-46.
12. Harel, I., and Papert, S. (1991). Constructionism. Norwood, NJ: Ablex.
13. Repenning, A. and Ioannidou (2004). Agent-Based End-User Development. Communications of the ACM, 47(9), 43-46.
14. Kuipers, B. (1986). Qualitative Simulation, Artificial Intelligence, 29: 289-388.