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Qualitative Reasoning techniques to support Learning by Teaching: The Teachable Agents Project

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Abstract

This paper describes the use of qualitative reasoning mechanisms in designing computer-based teachable agents that users explicitly teach to solve problems using concept maps. Users can construct the required problem-solving knowledge structures without becoming involved in sophisticated programming activities. Once taught, the agent attempts to answer questions using qualitative reasoning schemes that are intuitive and easy to apply. Students can reflect on the agent's responses, and then revise and refine this knowledge through visual interfaces. Preliminary studies have demonstrated the effectiveness of this approach.

Introduction

People have always believed that attempting to teach others is an especially powerful way to learn. This may be attributed to the fact that teaching involves a number of constructive activities, such as planning and organizing before teaching, explaining and demonstrating during the teaching activity, as well as analyzing and reflecting on student feedback during and after the teaching process. Researchers such as Bargh and Schul (1980) have shown that people who prepared to teach others to take a quiz on a passage learnt the passage better that those who prepared to take the quiz themselves.

More recently, a number of researchers have performed extensive analyses of the one-on-one tutoring process. For example, Graesser, et al.'s (1995) analysis of tutoring dialogues indicated that tutors teach by controlling student thinking and keeping them on track, and this promotes effective learning. Others have downplayed the role of the tutor, and focused on the student. The conjecture is that the one-on-one interactions in tutoring provide students many more opportunities for generative and constructive learning, and articulation of their self-explanations than a traditional classroom environment (Brown and Palinscar 1998; Chi 1997; Chan et al. 1992). Still others, for example, a recent study by Chi, et al. (2001), surmised that tutoring effectiveness should be credited to the joint effort of both tutor and student, i.e., the social interaction process is the key to improved student learning.

Extensive protocol studies by Chi et al. (2001) support all of the above observations. In terms of the interaction process, they found that students were to a larger extent responsible for initiating interactions. Also, responses elicited from the student in response to scaffolding questions by the tutor resulted in deeper learning than in situations where students were more involved only in self-explanation.

Studies conducted at the Learning Technology Center (LTC) at Vanderbilt University also indicate the students seem to benefit from activities in the teaching process (Biswas et al. 2001). For example, students preparing to teach made statements about how the responsibility to teach forced them to gain deeper understanding of the materials. Others focused on the importance of clear conceptual organization. Still others brought up the notion of how questions and feedback from students during the teaching process prompted deeper reflection and better understanding of the subject material.

A number of studies in the related field of collaborative learning have also shown that students learn more effectively when they work in groups that encourage questioning, explaining, and justifying of opinions (Cognition and Technology Group at Vanderbilt 1997). Reflection on these studies and others leads us to conjecture that creation of a computer-based system, where students can assume the role of "teacher" (and when necessary, switch to the role of "learner") may provide a motivating environment for learning and self-assessment. This prompted a full-scale study of the benefits of learning by teaching in a middle school science classroom. This project is briefly described next.

Previous Work

In 1998, Nancy Vye, a member of the Teachable Agents Group at Learning Technology Center (LTC), Vanderbilt University, conducted a set of design experiments with fifth grade students to study the effects of teaching on individual learning (Biswas et al. 2001). This experiment combined classroom instruction with a computer-based system developed for dynamic self-assessment and learning, the *STAR.Legacy* shell (Schwartz et al. 2000). The topic of study in this science classroom, titled *The River of Life*, was water quality monitoring in rivers.

STAR.Legacy employs inquiry cycles to integrate instructional techniques, resources, and a variety of self-assessment methods to encourage constructive learning and overcome inert knowledge. The STAR.Legacy interface for the River of Life Project, shown in Figure 1, adopts the generic step names from the Legacy cycle (Schwartz et al. 2000), and incorporates mechanisms that promote learning by teaching. Previous studies conducted by the LTC faculty members had shown the benefits of teaching preparation as much as the actual teaching process itself (Biswas et al. 2001). These two activities are seamlessly integrated into the STAR.Legacy cycle.

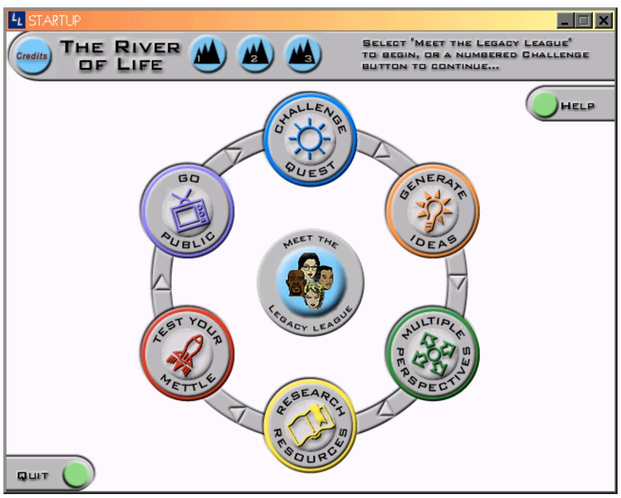

Figure 1: The STAR.Legacy interface for the River of Life project

In the River of Life project, the Legacy cycle starts with an introduction on streaming video to the animated character, Billy Bashinal, a high school student, who has been working with his friend, Sally, on a water-quality monitoring project. This project involves collecting and analyzing data from a local river, and writing up a water quality report. The introductory video shows Billy's negative attitude toward learning, and that results in sloppy work and very little effort put into the project. His attitude is made apparent when he tells Sally that their report should be good enough to earn a C grade.

At this point, the classroom is introduced to a set of cartoon characters, the D-Force, a group that has dedicated themselves to prevent students from making the same mistakes they had made in school. They confront Billy about his negative attitude, and convince him that he needs help. He is questioned about various aspects of river pollution monitoring, which makes the students in the classroom aware of Billy's deficiencies. The video ends with an appeal by the D-Force to the students in the classroom to help Billy improve his performance on the water-quality monitoring project. After this introduction the students enter the Legacy cycle, where they will learn about and help Billy solve a set of **Challenges**.

Each cycle starts off with a challenge, which is the problem that the students will teach Billy to solve. The students begin preparing to teach Billy by **Generating Ideas**, which requires them to make notes of important ideas that may be relevant to the problem at hand. This self-evaluation step allows students to be constructive and prepare for learning.

In the next step, students can access **Multiple Perspectives**. These are short nuggets of information provided by a set of experts that help the students to reflect on different aspects of the problem space (Spiro and Jehng 1990). This also helps them discover concepts important to problem solving that they had not thought of earlier (Schwartz et al. 2000). The information and clues that the students gather from this step provides them guidelines to perform **Research and Revise**.

In the *Research and Revise* step, students can access resources and tools that aid their learning of essential problem solving concepts and methods. This step combines a variation of learning tools, including computer simulations. Students work with these resources until they gain enough confidence and skills to teach Billy in the **Test your Mettle** step.

In the *Test Your Mettle* step, students take on the role of "teacher" by advising Billy on how to best answer a series of challenge-related questions. They see each question along with Billy's intended response and a set of alternative responses. They can either agree with Billy or suggest a better response from the set provided. Alternatively, they can defer giving any advice until they have consulted a compendium of online resources linked to the Teach-Billy environment. Following each question, Billy gives his "teachers" feedback on whether their advice enabled him to correctly answer the question.

In the *Go Public* step, students observe Billy re-solving the challenge. Note that Billy's performance here is prescripted. Hence, there is no direct link between Billy's competence and the students' performance during the Teach-Billy phase.

Despite the fact that Billy was only a pre-programmed, animated character, students who participated in this design experiment showed great enthusiasm to help Billy (Schwartz et al. 2000). This was evidenced in their comments during exit interviews, and was supported by data on their use of online resources in the Teach-Billy phase—students were highly motivated to access resources to ensure that they gave good advice to Billy. From these and other findings presented earlier, we concluded that social interactions in the form of teaching, even if virtual, could be a strong motivation for learning. Thus, we decided to build on this *learning by teaching* framework, and let students explicitly teach a computer agent. Once taught, the agent would reason about its knowledge and answer questions. The students could observe the effects of their teaching by analyzing these responses.

Unlike other work in Artificial Intelligence (AI) and agent technologies, our computer agents are not endowed with machine learning algorithms that learn from examples, explanations, or by induction. Our agent employs AI techniques to present students with an interface that enables them to input knowledge without having to do real programming[1]. The knowledge structures are primarily a causal graph that expresses relations between domain entities. To these structures the teachable agent applies simple reasoning mechanisms to answer questions posed to them, and generates explanations when asked to do so. The next section describes Betty's Brain, our current implementation of a teachable agent in the River of Life domain.

Betty's Brain

As discussed in the last section, our goal is to build an environment where students can explicitly teach and directly receive feedback about their teaching through interactions with a computer agent. To achieve this goal, we need a representation scheme for students to create their knowledge structure as a part of the teaching process. Realizing that our users are primarily middle-school students solving complex problems, this representation has to be intuitive but sufficiently expressive to help these students create, organize, and analyze their problem solving ideas. A widely accepted technique for constructing knowledge is the concept map[2] (Novak 1996, Spiro and Jehng 1990).

Several researchers have discussed the effectiveness of concept maps in promoting learning in scientific domains (e.g., Novak 1996; Novak 1998; Kinchin and Hay 2000; Stoyanov and Kommers 1999), by providing a mechanism for structuring and organizing knowledge into hierarchies, and allowing analysis of phenomena as cause-effect relations. The concept map provides a powerful tool to represent students' current understanding in a well-organized format (Kinchin and Hay 2000). Hence, concept map structures may provide a framework for reflection and revision of one's knowledge with the goal of achieving improved problem-solving performance. These high-order thinking skills may help to raise the students' motivation to gain a deeper understanding of a domain. Moreover, an intelligent software agent based on concept maps can easily employ reasoning and explanation mechanisms that students can easily relate to. Thus the concept map provides an excellent representation that serves as the interface between the student and the teachable agent. The rest of this section describes the design of our environment structured around these ideas.

The Concept Map

Novak defines a concept map, a collection of concepts and relationships between these concepts, as a mechanism for representing domain knowledge (Novak 1996). In our environment, concepts are **entities** that are of interest in the domain of study. For example, common entities in a river ecosystem are fish, plants, bacteria, dissolved oxygen, carbon dioxide, algae, and waste. Relations are unidirectional, binary links connecting two entities. They help to categorize groups of objects or express interactions among them.

In the current implementation of domain knowledge, such as for a river ecosystem, students can use three kinds of relations, (i) **cause-effect**, (ii) **needs**, and (iii) **hierarchical** relations to build a concept map. The primary relation students use to describe relations between entities is the causal (cause-and-effect) relation, such as "Fish eat Plants" and "Plants produce Dissolved oxygen". The causal relations are further qualified by **increase** ('+') and **decrease** ('−') labels. For example, "eat" implies a decrease relation, and "produce" an increase. Therefore, an introduction of more fish into the ecosystem causes a decrease in plants, but an increase in plants causes an increase in oxygen.

The "needs" relation is similar to the cause-effect relation. It also expresses a dependency, but the change in one entity does not cause a change in the other entity. For example, a number of students in our classroom study created the relation, "Fish live by Rocks". In this case, the "live by" relation is categorized as a need relation. Fish use rocks, but an increase or decrease in fish does not directly change the amount of rocks. Other more complex forms of the "needs" relation, e.g., "Plants need Sunlight to produce Dissolved Oxygen" have not yet been implemented in Betty's Brain.

Hierarchical relations let students establish class structures to organize the domain knowledge. Consider an example where students deal with a variety of fish, such as trout, bass, blue gill, and catfish. All of these fish types breathe dissolved oxygen and eat plants. To simplify the knowledge construction process, students can first create the entity "Fish", and express the "Fish eat Plants" and "Fish breathe Dissolved oxygen" relations. Then, they can create individual fish entities, such as "trout" and "bass", and link them to the "Fish" entity using "is_a" links. All relations associated with Entity "Fish" are inherited by these individual types unless they are over-ridden by more specific links (Russell and Norvig 1995).

[1] If there were not the case, our approach would be impractical and infeasible, especially for middle school students.
[2] In particular, the concept map technique developed by J.D. Novak (1996)

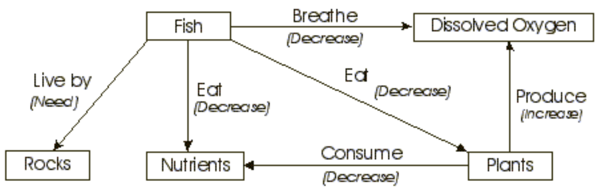

Figure 2: A partial concept map

A partial concept map created by a student is shown in Figure 2. The labeled boxes correspond to entities (the labels are entities' names), and the labeled links correspond to relations. The arrow indicates the direction of the relation, and its name appears by the arrow. The parenthesized phrases indicate the relation type.

Reasoning Process

Our teachable agent, Betty, uses a reasoning mechanism that allows her to apply and analyze the knowledge the student has taught her in the form of a concept map. Our goal is to set up an interaction process, where after being taught, Betty tries to answer relevant questions in the domain. The students observe Betty's answers, and can query Betty further to get a more detailed explanation of how the answer was generated. In addition, Betty often makes comments about the correctness of her response. Examples of such comments are "*The teacher said that this answer was not quite correct.*" and "*I checked with John, and he said that …*". This prompts students to revisit and reflect on the knowledge structures they have created, and try to improve them, if necessary.

The reasoning mechanism is based on a simple chaining procedure to deduce the relationship between a set of connected entities. To derive the effect of a change (either increase or decrease) in Entity A on Entity B, the teachable agent performs the following steps:

1. Generate all possible paths from Entity A to Entity B.
2. For each path, propagate the effect of the change in Entity A along the path by pairwise propagation (i.e., follow the link from Entity A to its effect) and use the table in Figure 3 to derive the resulting increase or decrease on the effect entity. If a "needs" relation appears along the path, this results in propagation a "no change" effect. Repeat this process until we have a result for Entity B.
3. Combine the results from all paths, and interpret the final result.

Change	Relation	Result
+	+	+
+	□	□
□	+	□
□	□	+

Figure 3: Pair-wise effects

For example, assume that the student asks the teachable agent to deduce the effect of an addition of fish to the ecosystem on nutrients using the partial concept map shown in Figure 2. Searching the concept map, Betty discovers two possible paths:

1. Fish – *eat* – Plants – *consume* – Nutrients
2. Fish – *eat* – Nutrients

For each path, the agent starts with the initiating entity and computes the result on the end entity by sequential propagation (Step 2 above). For example, the change, more fish (+) propagated through the relation "eat" (–) produces a decrease (–) in plants. The chaining process continues on the path, and a decrease in plants (–) with the relation "consume" (–) results in an increase (+) in nutrients. The same reasoning process is applied to paths 2 to get a decrease (–) in nutrients as shown below:

1. Fish (+) *eat* (□) Plants (□) *consume* (–) Nutrients (+)
2. Fish (+) *eat* (–) Nutrients (–)

When some paths imply an increase (+) and others a decrease (–), one cannot derive a definitive increase or decrease result. To keep things simple for middle school students, this version of Betty's Brain concludes that there is an overall increase if the number of increase paths is greater than that of decrease paths, or an overall decrease if the reverse is true. The result cannot be determined if the numbers of increase and decrease paths are equal. Thus, for this example, Betty concludes that she cannot say if there is a net increase or decrease in nutrients.

The current simple reasoning mechanism proved to be quite effective, but students were not satisfied with inconclusive results, as we discuss below. Along with the final result, Betty also displays how the answer is derived by animation on the concept map.

To test the effectiveness of this approach, two of the authors, Schwartz and Wang, ran a pilot study on a class of 20 undergraduate students majoring in Psychology at Vanderbilt University. Each student was asked to "teach" his or her own Betty to be a consultant to help people think about the high-level things that would help or hurt the chances of getting a job (e.g., dressing well, studying, socializing, etc.). At various points, a student's Betty was shown on a class-projection system and asked a question (e.g., "If studying increases what will happen to the chances of securing a good job").

Even though Betty did not have a discernable personality, the results were very encouraging. Students were exceptionally attentive to the "front of the class" tests and spontaneously discussed Betty's answers and asked to see her reasoning unfold. The activity also proved to be very motivating to the students. Even though they knew we had not implemented a "save" function at this point, 65% of the students continued to work on their Betty's for an hour after class, until they finally had to vacate the lab.

Importantly, the students had little trouble learning how to teach and generate questions for Betty. This only took about 5 to 10 minutes, and was sufficient for students to learn about knowledge organization based on Betty's visual representation. For example, the students were surprised that there were multiple and conflicting cause-effect pathways. They started with the "youthful" assumption that causality is univocal. In one Betty, for example, the student discovered that increasing "study time" increased "knowledge" which increased "chances of getting a job." But the student had also taught Betty that increasing "study time" decreased "social skills" which reduced "chances of getting a job." Competing pathways were not something the students had anticipated, and it led some students to ask if there were ways to qualify the amount of increase or decrease by specifying weights. This led to our implementing a more sophisticated qualitative reasoning scheme that is described in the next section.

The students also felt that the animation mechanism by itself was not a sufficient illustrator of the reasoning process. They wanted a more structured text form of explanation that they could study and reflect on. Thus, we added a hypertext-based explanation mechanism to the next version.

Extending Betty's Brain

In our pilot study of Betty's Brain described above, some students were confused about Betty's behavior because she seemed not to make any conclusion if there were competing pathways. Figure 2 illustrates an example of such a situation in the ecosystem domain. As discussed previously, Betty could not conclude what would happen to nutrients if more fish were added to the system.

Another confusion occurred when the bacteria entity was added to the partial concept map in Figure 2 (see Figure 4), and Betty gave the same answer about the effect of adding more fish on dissolved oxygen (a decrease) based on both concept maps. This led the students to believe that Betty was not considering the effect of adding bacteria to the concept map.

Our solution to this problem was to make the qualitative reasoning more fine-grained by letting the user qualify the degree of change as "small", "normal", or "large". The modified pair wise chaining procedure is shown in Figure 5, where '$+_L$', '+', and '$+_S$' represent large, normal, and small increases, respectively, and '$-_L$', '−', and '$-_S$' represent large, normal, and small decreases, respectively.

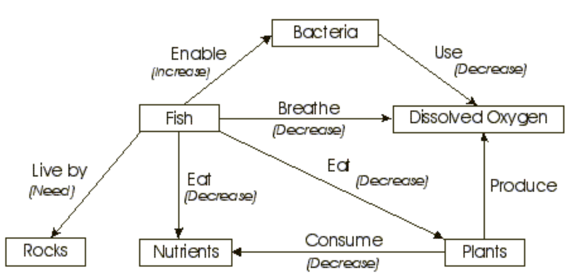

Figure 4: The partial concept map with Entity bacteria

Change in Relation

Ch

	$+_L$	+	$+_S$	$-_S$	−	$-_L$
$+_L$	$+_L$	$+_L$	+	−	$-_L$	$-_L$
+	$+_L$	+	$+_S$	$-_S$	−	$-_L$
$+_S$	+	$+_S$	$+_S$	$-_S$	$-_S$	−
$-_S$	−	$-_S$	$-_S$	$+_S$	$+_S$	+
−	$-_L$	−	$-_S$	$+_S$	+	$+_L$
$-_L$	$-_L$	$-_L$	−	+	$+_L$	$+_L$

Figure 5: The extended pair wise effects

Suppose that all the relations in the concept map in Figure 4 are specified to be normal changes, except for the relation "Fish eat Plants", which is classified as a "small" decrease. A more precise explanation can now be generated for the same question applied to this concept map:

1. Fish (+) *eat* ($-_S$) Plants ($-_S$) *consume* ($-_S$) Nutrients ($+_S$)
2. Fish (+) *eat* (–) Nutrients (–)

In this case, Betty concludes that adding more fish in the ecosystem causes a small decease in nutrients.

Similarly, when the question "What would happen to dissolved oxygen if we add more fish?" is asked of Betty without bacteria, she answers that there is a normal decrease in dissolved oxygen (by combining a normal decrease with a small decrease). However, when the bacteria entity is included, Betty concludes that dissolved oxygen would "decrease a lot" (the resultant combination of two normal decreases plus one small decrease).

Current System

The interface of Betty's Brain, displayed in Figure 6, is implemented in Java with Java Swing components, and can be accessed via the World Wide Web[1]. The environment has three main parts: (i) the concept map and its editing panel, (ii) the reasoning process and its visual interface, the explanation panel, and (iii) the dialog panel for interactions between Betty and the user.

Students create, edit, and modify the concept map using features provided in the editing panel. At any point, the user can initiate the question panel by clicking on the "Ask Betty" button. The question panel, shown in Figure 7, has templates for three question types:

Type 1: If *Entity A* increases/decreases, what will happen to *Entity B*?
Type 2: If *Entity A* increases/decreases, what will happen?
Type 3: What can cause *Entity B* to increase/decrease?

Once the user has created a question, they click on the "Get Answer" button. This initiates the animation that displays the search process as the reasoning system generates its answer. Following the animation, the textual

[1] URL: http://macs1.vuse.vanderbilt.edu/betty/classes/.

explanation appears in the explanation panel as Betty's response. This explanation panel employs a mini-web-browser in Java Swing to structure the explanations in a hypertext form. Students first get an overall summary of the answer and a list of the paths that contributed to the solution. They can then click on an individual path to obtain more detailed explanation. Together, the animation and explanations enable students to compare and contrast their thinking with the agent's reasoning process, and this often helps them to articulate their understanding of the relevant concepts (Chi et al. 2001).

Below is a detailed trace of the explanation mechanism for a type-2 question applied to the concept map in

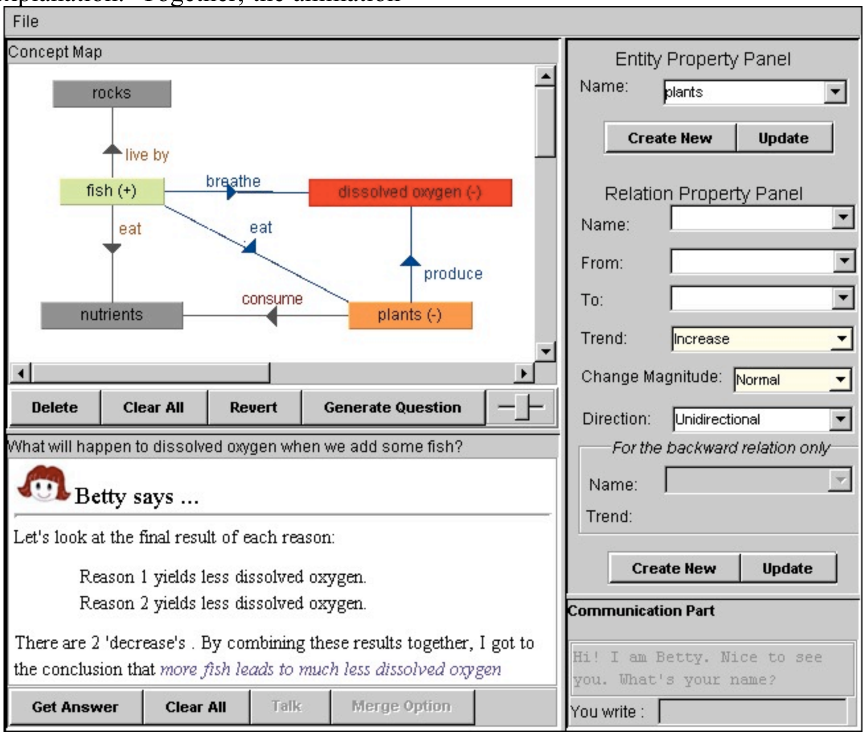

Figure 6: The current Betty's Brain Interface

Figure 2. The explanation for the question, "*What will happen when we add more fish?*", starts with the following paragraph:

> I found that if we add more Fish, the following things could happen:
>
> Effect 1: Plants decrease.
> Effect 2: Dissolved Oxygen decreases a lot.
> Effect 3: Nutrients are about the same.
>
> I can explain in more detail if you click on the effect you are interested in.

When the user clicks on an individual effect, more details will be shown in the format of the explanation for the first type of questions. For example, the following passage is displayed when the user clicks on the second effect:

> I found that **Dissolved Oxygen decreases** if Fish increase. Here is how I get the result:
>
> Reason 1: [Fish - Plants - Dissolved Oxygen] --> Dissolved Oxygen decreases a bit.
> Reason 2: [Fish - Dissolved Oxygen] --> Dissolved Oxygen decreases.
>
> I can explain in more detail if you click on the reason you are interested in. If you want to know how I deduce the final result, click here.

The link for each reason leads the user to the explanation that is similar to the chaining procedure described in the previous section but in a natural language. The last link in the passage, "click here" shows the details of the overall conclusion generated by the qualitative reasoning mechanisms (see the explanation panel in Figure 6).

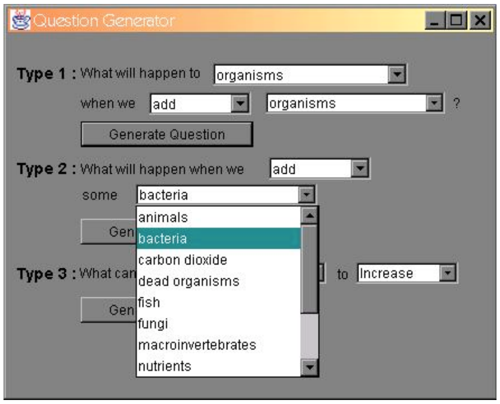

Figure 7: Question Generator

We conducted a second pilot test on the updated system focusing on the effectiveness of the concept map and how Betty's explanation mechanisms helped the leaning and understanding process.

Pilot Tests

The second study, conducted at Stanford University by Dan Schwartz, more directly shows how Betty's visual knowledge representation shapes student self-assessments and their consequent learning. This work complements research that demonstrates the benefits of concept mapping on learning (Kinchin and Hay 2000; Novak 1998; Stoyanov and Kommers 1999). However, Betty's Brain differs from most concept-mapping activities, because it enforces specific types of relationships that students might otherwise violate in paper and pencil activities, and it shows the implications of those relationships. We specifically wanted to explore Betty's effects on knowledge of causal relationships and how she affected student's self-assessments and learning. As a simple source of contrast, we included a control condition in which students completed the familiar instructional activity of writing a summary. (We would have used concept mapping, but these students had not had instruction in concept mapping.) Sixteen older teenagers completed the experiment either in the Summary or Betty condition. They each worked individually, so we could collect their think aloud protocols. In each condition, students began by reading a four-page passage on exercise physiology. We removed the passage and asked the eight students in the Summary condition to write a summary about cellular metabolism. We got them started by suggesting they should write about things like the relationship between mitochondria and ATP resynthesis. In the Betty condition, we asked students to teach Betty about cellular metabolism after showing them how to teach Betty a relationship and how to ask a question.

As in the previous study, every Betty student wanted to continue working past the cut-off point, compared to zero students in the Summary condition. The more novel findings involve self-assessment and learning. With respect to self-assessment, 75% of the Betty students compared to 12.5% of the Summary students realized that they had been thinking in terms of correlation rather than causation. For example, one student realized that he did not know whether mitochondria increase ATP resynthesis or whether it is the other way around. Similarly, the Betty students discovered they were not sure which things were processes and which were entities. These self-assessments had positive effects on students' subsequent learning.

After the students stopped summarizing or teaching, we asked them to reread the physiology passage. Afterwards, we reclaimed the passage and asked the students what, if anything, they had learned from the second reading. Students in the Betty condition reported 2.9 cell metabolism relationships on average, compared to 0.75 for the summary condition. Finally, we gave the students a sheet with a few key words, like mitochondria and oxygen. For each word, we asked them to "list relationships it has to other entities or processes in cellular metabolism." The students in the Summary condition tended to assert single relations; for example, "mitochondria increase ATP resynthesis." The Betty students tended to assert chains of two or more relations; for example, "mitochondria with glycogen or free fatty acid increase ATP resynthesis." Overall, the Betty students produced 3.75 chains of two or more relations, whereas the Summary students produced 1.0 on average.

These results demonstrate that the visual concept-mapping mechanisms our environment employs can help students structure their knowledge in accordance with an external representation. Developing chains of causal relationships is exactly what Betty requires of students.

Currently, we are conducting another study that focused on the reasoning about and debugging concept maps. In this study, students were first shown a model ecosphere, and then asked to construct a concept map that included the entities and relation that governed the ecosphere behavior. In the second part of the study, students were given a buggy concept map and a set of questions for which Betty generated incorrect or incomplete answers. The students were asked to study the answers, and then used the information to correct Betty's concept map structure.

As before, students had very little trouble learning the concept map structure and using the environment for creating the knowledge structures, generating questions, and analyzing Betty's responses to questions. Preliminary analysis of the results shows that the students who used the question-answer and the explanation mechanisms frequently, while generating their concept maps tended to create richer and more complete concept map structures. They were also more successful in the debugging tasks in Part 2. In the feedback provided, the students overwhelmingly asked for more resources to gain better understanding of the domain so that they could teach Betty more precisely. This again is a very positive indication that the teachable agent environment encourages students' learning and self-assessment. We will provide more detailed results of this experiment as they become available.

Summary and Conclusions

Our preliminary studies with the Betty's Brain system demonstrate its effectiveness in promoting learning and self-assessment among students. Our goal is to develop it as a general teachable assistant that can be applied to a variety of scientific domain, where the reasoning of causal-effect structures is important to learning about the domain. Our studies also show that students have little trouble and require very little instruction in using the system for creating their knowledge structures and using the question-answer mechanism. More extensive studies need to be conducted on middle school students, our ultimate target group for this project.

The studies also indicate a number of extensions that we need to incorporate with our knowledge structure and qualitative reasoning mechanism. The extensions required for the "needs" relation were discussed earlier in this paper. We also need to add bi-directional causal links to make the concept map structure more expressive and realistic. Consider the link, "Fish breathe Dissolved Oxygen". The addition of fish cause a decrease in the amount of dissolved oxygen. However, this particular link also conveys that a decrease in the amount of dissolved oxygen should adversely affect the fish population. In the next version of they system, students will be allowed to create bi-directional links. This will require changes in the reasoning mechanism to ensure that cycles created by the bi-directional links do not result in infinite reasoning loops.

We are currently studying ways in which temporal information can be added to the reasoning mechanism so that the system can explicitly reason about multiple cycles that take place over a period of time. Once this is in place, the qualitative reasoning structures in Betty's Brain can be linked to qualitative simulation programs that provide students with a more realistic picture of a system's behavior. Designing and developing these features for middle school students will be a difficult but very exciting challenge.

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