

The Evolution of the Intellectual Partnership with a Cognitive Tool in Inquiry-Based Astronomy Laboratory

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Abstract. This paper describes a study focused on the longitudinal application of a cognitive tool by observing a pair of learners' interaction with it over a semester. This study intended to develop a deeper understanding of the process whereby learners become more capable of engaging in scientific inquiry with the tool in order to advance technology-enhanced, inquiry-based approaches to instruction. In an effort to understand how learners move toward coherent knowledge structure, eccentricity of planet's orbit emerged as one of the main themes. The findings are discussed focused on how the pair used, understood, and elaborated the concept of eccentricity.

Keywords: Distributed cognition, expertise, cognitive tool, inquiry-based learning, modeling

Inquiry-based pedagogies focus on the question of how people solve problems and create explanations about the world (Greeno, Collins, & Resnick, 1996). Advances in technology have introduced computerized modeling and visualizations to scientific inquiry practices, which can be considered as cognitive tools of scientists. Hoping for the result of better instruction, recent research examines how the inclusion of technology in inquiry-based learning supports people's inquiry processes. Adopting these tools for educational use has a lot of advantages in engaging students in cognitive activities that are similar to those of scientists.

The failures of adopting this approach come from our assumption that learners will automatically have rich experiences as novice scientists (Pea, 1993; Perkins, 1993). The intervention of modern inquiry tools does not guarantee learners' engagement in modern scientific inquiry. It often gives learners multiple challenges of understanding the tools and inquiry processes in addition to the scientific contents. However, there are not sufficient investigations regarding how learners come to use tools in profound ways, how learners' growing expertise in use of tools for scientific inquiry impacts their development of intellectual partnership with it, and how this partnership evolves over time. As a result of the partnership, the ways in which students construct their understandings with their tools should become consistent with scientists' practices. Therefore, questions about learners' development of cognitive partnerships should be explored to adopt these approaches in the classroom.

The purpose of this study was to develop a deeper understanding of the process whereby learners become more capable of engaging in scientific inquiry with a computer tool over time. A second goal was to learn how to improve technology-enhanced, inquiry-based approaches to instruction. We assumed that modeling-based inquiry and the use of the Astronomicon program would result in students' acquiring practices that resemble those of scientists. With the theoretical belief that a certain activity, like an inquiry, task forms a particular kind of a learner-tool joint system, the overarching research question was this: Over an entire semester how do groups gain expertise in the use of the tool for scientific inquiry and develop intellectual partnership with it?

CONCEPTUAL FRAMEWORK: COGNITIVE TOOLS FOR SCIENTIFIC THINKING

Cognitive tools can be defined simply as aides for cognitive tasks such as complex calculations (Lajoie, 1993) or more sophisticatedly as "technologies that enhance the cognitive powers of humans during thinking, problem solving, and learning" (Jonassen & Reeves, 1996). The theoretical foundation of cognitive tools comes from the theory of distributed cognition, which regards cognition as residing not only in a person's head, but distributed among people, artifacts, and symbols (Salomon, 1993b). A computer becomes a cognitive tool when it performs cognitive tasks together with learners. Computer is no longer perceived as a mere delivery medium, but as a tool with unique capabilities that complement learners' cognition (Kozma, 1991). As computers have been described as "partners in cognition" (Salomon, Perkins, & Globerson, 1991), we regard learners and cognitive tools as intellectual partners that have reciprocal interactions during learning activities. The conceptual framework of this research started with the ideas of distributed cognition and was elaborated with the *theory of expertise*.

Expertise is diversely defined as a standard of expert performance (Ericsson & Smith, 1991), as a relative degree of excellence for an activity (Salthouse, 1991), and as some degree of proficiency in our everyday activities (Carlson, 1997). Experts rely on the environment and technology, and capabilities of using them are part of their expertise (Stein, 1997). Within the field of instructional technology, however, expertise has been discussed and employed mostly in such areas as intelligent tutoring systems and expert systems. These systems model and perform the experts' cognitive processes. In contrast to the approach to represent the expert processes, we should focus more on the roles of technology in experts' practices.

The expertise view of technology adds specificity to the distributed notion in that the technology becomes one of the most important assets of the involved activities. With these two theories together, the interactions among

learners and tool within an activity represent the expertise of the distributed cognitive system. In other words, cognitive tools can be regarded as having some kind of expertise, forming a joint system of learning.

Joint Learning System for Scientific Inquiry

Cognitive tools for scientific inquiry are developed by emulating or modifying scientists' tools. These tools complement the scientific investigation process during the learners' inquiry as if experts use computers for their professional activities. The main purpose of a cognitive tool varies from organizing and representing learners' thinking to creating actual products (Ericsson & Smith, 1991; Perkins, 1993). Activities using cognitive tools should promote the ways in which tools are used in the world because the capabilities of a tool become worthwhile only because of the activities the tool affords (Salomon, 1993b).

How a joint learning system works in concert with scientific inquiry should then be given significant emphasis for our research and development. The Learning Through Collaborative Visualization (CoVis) project, for example, has gone through the iterations of research and development in order to promote open-ended inquiry within constructivist learning environment (Edelson, Pea, & Gomez., 1996). The major component of the CoVis project is its investigation tools for learners, such as World Watcher. World Watcher allows users to select units, examine visualizations at varying scopes, customize the display of visualizations, and analyze and create data with mathematical operations or other metaphors (Edelson et al., 1999). This opens up a novel opportunity for learners to dynamically observe different parts of the world, which is impossible to do without such tools. In their global warming curriculum, students prepared briefings of their investigations for a fictitious international conference, providing authentic experiences as novice scientists (Edelson et al., 1999).

Development of the Joint Learning System

The cognitive growth of an individual cannot be understood without understanding the development of joint relationships, because a person's growth is indeed the result of the distributed work with the environment (Karasavvidis, 2002; Salomon, 1993b). The outcomes of cognitive tasks include not only constructed knowledge or performance, but also resulting cognitive process and distributed structure, which are important parts of the cognitive development (Salomon, 1993). When the participants of distributed cognition continually work together, this particular distributed system is likely to develop into a stronger one. Individuals discover more affordances of the tool and even bring out more abilities of themselves as they develop the distributed relationships. Therefore, the tool and learners better contribute to the performance (Pea, 1993).

This idea of joint learning system development becomes much more perceptible by applying the concepts from the theory of expertise. The elements characterizing performance of experts can be summarized as *knowledge*, *functions*, and *representations*. Experts process their knowledge during performance from more deductive ones (e.g., rules and formulas) to more inductive ones (e.g., information about exemplars) (Patel & Groen, 1991). They use cognitive functions varying from simple information search and rule execution to higher-ordering thinking and problem solving (Ericsson & Charness, 1994; Perkins, 1993). Experts generate complex representations about problems they encounter, which provide images to support constant reflections on and improvements in their decision making and actions (Ericsson, 1996; Glaser, 1996; Winn & Snyder, 1996). These three elements work together with significant roles in expert performance and development. In developing expertise, especially in early stages, one should develop a basic structure of expertise in the domain, which involves better use of a learner's cognitive functions, gained knowledge structure and external representations, and some automaticity in the performance processes (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996).

Knowledge

In structuring knowledge, novices first make cognitive efforts to understand the nature of tasks in the domain and to find important information and then to organize their knowledge into more accessible structures (internal representation of knowledge) (Schneider, 1993). To develop expertise, learners constantly face problems that challenge the current level of knowledge and competences, requiring them to reorganize the existing fragmented knowledge and connect with new concepts. Cognitive functions are better facilitated for use when knowledge is organized in a coherent way (Glaser, 1996). As a joint learning system, learners' knowledge, the tool, and the current setting (activity and environment) are organized and accessed at the time of performance. This organization changes each time they come together as their activity changes and their knowledge develops.

Functions

The learners' growing expertise in the domain and increasing familiarity with the tool are important to perform better in inquiry activities. The partnership of the joint system remains weak for some time, and then learners gradually make more effective use of the tool, developing into a stronger joint system (Pea, 1993). Suggested by scholars in distributed cognition, higher-order thinking such as problem-solving and pattern recognition and executive functions such as deciding what to do and where to go are the main roles of the learners to perform tasks (Perkins, 1993). The technology processes rules, such as producing representations with inputs and retrieving information, but cannot understand the meanings of representations and activities (Salomon, 1993b).

Novices approach problems with strategies that are based more on concrete information, and then they use more abstract reasoning as they gain expertise (Anzai, 1991; Patel & Groen, 1991). Novices rely on the surface features of the problem, commonsense knowledge, and trial-error approaches due to the lack of their domain-specific knowledge base. They start using a weak method, which uses observation and problem reduction, instead of starting with underlying principles. Experts approach problems with a strong method, using a working hypothesis and relying on the systematic representation and their domain-specific knowledge (Anzai, 1991; Patel

& Groen, 1991). Experts focus selectively on relevant information and switch between weak and strong methods depending on the problem (Anzai, 1991; Patel & Groen, 1991; Scardamalia & Bereiter, 1991). The processes of giving selective attentions and using appropriate strategy are automatized by repeated performances on problem-solving, which enable them to use their cognitive resources to the novel aspects of a problem (Schneider, 1993). With gained expertise, learners would no longer need to make cognitive efforts to understand the tool itself, but the cognitive functions of the learners and the tool should become well-coordinated to perform a task.

Representations

The ability to use external representations of knowledge and cognitive process plays an important role in the performances of many domains (e.g., Anzai, 1991). The internal structure of knowledge is often revealed and enhanced by the development of external representations, which learners use more efficiently with more expertise (Patel & Groen, 1991). Especially in science, one of the important inquiry approaches nowadays is to find patterns using visual representations, such as modeling and visualizations (Pagels, 1988). As a joint system, learners and the tool produce visual representations together, which are used not only to help others to understand their findings, but also to help themselves to reflect on their activities (Glaser, 1996).

RESEARCHING THE DEVELOPMENT OF THE JOINT LEARNING SYSTEM

This study intended to examine some of the assumptions about the joint learning system based on the above conceptual framework (a detailed discussion on this framework can be found in Kim & Reeves, in press; a relevant study can be found in Hay, Kim, & Roy, in press). First, cognition is distributed within a joint learning system during students' learning (Salomon, 1993). Second, the way a joint learning system develops through students' extended learning experience could be similar to the learning process of developing expertise by gaining knowledge structure, problem-solving strategies, and automaticity (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996). Third, the primary expertise components of a person are knowledge, functions, and representations, and those of a joint learning system can be regarded as the same (Ericsson & Charness, 1994; Patel & Groen, 1991; Perkins, 1993). The main questions were: 1) How does the joint learning system develop intellectual partnership? 2) How does it gain expertise over an entire semester in scientific inquiry using the tool?

Research Set-up

As an undergraduate astronomy reform effort at the University of Georgia, the Virtual Reality Modeling Project (VRMP) implemented a unique learning approach to an introductory astronomy lab. It covers basic astronomy concepts of orbits, time, phases, eclipses, and seasons. This course is characterized by a modeling-based inquiry (MBI) pedagogical approach and a three-dimensional (3D) model construction tool called Astronomicon. Learners build and simulate their own models of solar systems within Astronomicon's 3D environment (see Figure 1). The learner-created models are used not only as surrogates of our solar system, but also as experimentations of nonexistent systems. Modeling tools become very powerful when students build models with underlying principles and dynamically modify them while running and observing them. Learners gain a fundamental understanding about the system through reasoning to make models and observing their created patterns (Kozma & Shank, 1998; Penner, 2001). Figure 1 shows the overhead view of the Earth (at the center) and the moon orbiting around the Earth—the big circle is the moon's orbital disk. Astronomicon modeling interface (Figure 2) facilitates learners' creation of models.



Figure 1. Astronomicon (overhead view of the Earth)

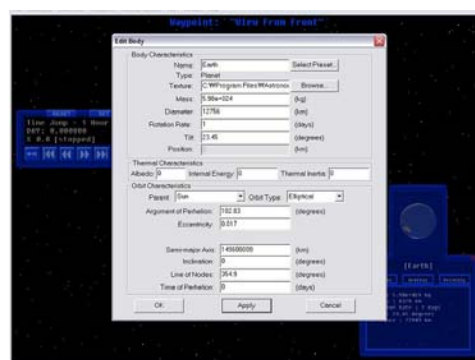


Figure 2. Astronomicon modeling interface

Learners worked collaboratively in pairs throughout the semester with an individual laptop computer. They usually used one of the computers for modeling and the other for information search within a group. In this study a pair of students was examined as a case to focus on the transitions and changes of their learning. The in-class observation was focused on the overall process, and the detailed interaction was analyzed using the video data. This required an in-depth investigation of the learning process and development, for which a complex digital system was used for data collection and analysis. Integrated Temporal Multimedia Data (ITMD) research system (Hay & Kim, in press) records, stores, and simultaneously plays the activity of each group, screen captures of the computer, and the voice of each participant. This approach provides unlimited access to the detailed interactions among learners and technology, maintaining a contextual richness close to the original. For this study a camera was set up for the group, and an extra camera was at the back of the classroom to capture any events happening beyond the group level. Other sources, such as learners' lab notes and written reports, provided a more complete

understanding. The results of pre/posttests indicated overall improvements in basic astronomy knowledge. Test items were focused on light and planetary motion selected from three previously developed and validated tests: Force Concept Inventory (Hestenes, Wells, & Swackhammer, 1992), Project STAR-Astronomy Concept Inventory (Sadler, 1998), and the Astronomy Diagnostics Test (Zeilik, Schau, & Mattern, 1998).

Betty and Allen

The pairs were randomly formed or assigned at the beginning of the semester, and this group (Betty and Allen) was selected based on the overall attendance and the working relationship between the two. Even though learners were paired to work together, some chose to work individually, some dominated the work, and/or one of the pair had too many absences to make any contribution. The other factor of the selection was the balance between the two learners, including their confidence level, being co-ed, and interest and knowledge about astronomy.

Betty was taking the lab as her first college-level astronomy as a sophomore, whereas Allen was a senior retaking the course after several years. Both were social science majors. Betty was somewhat interested in astronomy whereas Allen read magazines and books about astronomy and was interested in furthering his understanding of the universe. Betty did not feel confident in the pretest, in which she correctly answered about 38 percent (the class average was approximately 44 percent). Allen felt confident enough to do the lab work, but was uncertain about how well he did on the pretest (53 percent correct), which showed some misconceptions. Betty had the common misconception that the seasons are caused by the changing distance between the Earth and the sun due to the Earth's elliptical orbit around the sun. Similarly, Allen related the idea of Earth's tilt with the distance to sun (parts of the Earth would get closer when they are tilted toward the sun).

EVOLVING EXPERTISE AND PARTNERSHIP

The potential roles of the learner(s) and the tool as intellectual partners are implied by knowledge, functions, and representations embedded in the tool and the learner activities. The framework of the expertise structure guided the analysis within a meaningful chunk, such as modeling and observing lunar phases, exemplified in Table 1. Learners gather information to create their models, make decisions on the models and observations, and gain knowledge about the solar system. Learners use and produce various representations to assist their process. With the embodied rules, the tool provides the modeling interface that can collect and operate the inputs from learners. This knowledge and functions of the tool eventually contribute to the working representation of a system, which is continuously modified or viewed from different perspective throughout the modeling and observation process.

Table 1. The Expertise Structure of the Joint Learning System

	Learner(s)		Tool (Astronomicon)	
	Defined	Example	Defined	Example
Knowledge	Provided/Acquired information; prior/acquired knowledge and understanding	Data of the Earth and the moon (size, mass, etc.); cause of the phases	Rules embodied in the software	Three-dimensional configuration of the space
Functions	Decisions about modeling and observations; inquiry strategies	Observing the moon from the Earth; trial-and-error	Operations performed with learner inputs	Producing planetary motion of the moon around the Earth
Representations	Provided/gathered information materials; sketches/notes/reports; images from Astronomicon	Solar system data sheet; images of the moon going through phases seen from the Earth	Modeled system processed with learner inputs	Modeled reality from a specific viewpoint (the moon seen from the Earth)

Novices are characterized by their fragmented knowledge structure and weak approaches to the problems, which may turn their attention to tangential or unimportant aspects of the situation (Alexander, 2003). During the process of learning with Astronomicon, learners transform their fragmented factual knowledge from lectures and textbooks into an experienced one, situated in a coherent structure. During their initial model exploration with Astronomicon, Betty and Allen focused on surface features, practiced trial-error approaches, and depended on their common senses, as are characteristics of novices (Anzai, 1991; Patel & Groen, 1991). A typical mistake, coming from their underestimation of the space scale, was to make the distance between objects too short. Their initial models had objects being inside of their parent objects or orbiting in and out of it. They started changing properties, such as semi-major axis (the distance from the planet to its parent object) and eccentricity. Betty and Allen also maintained their interest on the surface features and their manipulations at the beginning. When first practicing model building, Betty made planets with various available planet textures and gave them cute names like Blue and Sharpie. When they first worked together and made four different Earths, Allen applied multiple kinds of Earth's textures to the planets (e.g., the Earth's topographical image, the satellite image with clouds, and images with different resolutions).

We explored the interactions within the joint learning system in order to understand the evolving expertise structure and overcoming novice traits. Working as a pair with one computer, learners also negotiated their roles within the team and went through the familiarization process with the 3D tool. We will focus our discussion on the growth of the expertise structure outlined above; nonetheless, the role negotiation and tool familiarization process are inherently part of the episodes. One of the constructs that determine the planetary motion of the solar system is *eccentricity* (the extent to which an elliptical orbit departs from a circular one. Eccentricity ranges between 0 and 1, 0 being a circle.). Eccentricity was the very first concept that learners explored in the class and continuously dealt with for their inquiry and was emerged as one of the main themes that continuously appeared. As one of the examples of the change in knowledge structure and inquiry approaches of the joint learning system, we will look at how Betty and Allen used, understood, and elaborated the concept of eccentricity.

Episode One: Making Meanings of Eccentricity

On the first day of working with Astronomicon, learners were asked to explore the differences made by changing the orbital eccentricity: *What is eccentricity?*

- Create a sun with four almost identical planets.
- The only difference should be the eccentricity.
- Explain the concept of eccentricity to your instructor using the taken data (pictures).

Before doing this activity, *eccentricity* (ϵ) was a word without much meaning, and its input values were numbers without any concept association. Watch Betty and Allen first started playing with Astronomicon:

1. [Betty keeps getting error messages when clicking on OK button, trying to finish adding a new planet. Error message: Please enter a number between 0 and 1.]
2. Betty: Huh... between 0 and 1... Is my eccentricity wrong? [currently 5]
3. Allen: Yes. Because eccentricity 1 means circle. To make it elliptical you have to make it less than 1.
4. Betty: Could be that? [putting in .00002].
5. Allen: You can try. I don't see why not. I guess that's the whole point of the program.

Earlier in class, Betty had trouble with her input for eccentricity [1-2]. Allen gave her the right value range (<1), but incorrect information that eccentricity 1 meant a circle [3]. Allen had a much better sense of the concept, knowing that eccentricity values had to do with shapes. At this point, however, the input of the .00002 value did not mean more than a random experiment to Betty, nor did to Allen [4-5].

Later, when they worked on the above task together, Betty and Allen started to make the connections between the numbers and the actual shapes of the orbits. Their initial model consisted of the four planets whose eccentricities were very close to zero (E1, $\epsilon=.01$; E2, $\epsilon=.03$; E3, $\epsilon=.05$; and E4, $\epsilon=.07$). All four planets were closely lined together, almost overlapping with each other [6-11].

6. Allen: I don't know what that did. I guess we will find out.
7. Betty: I guess maybe it is hiding behind another one, maybe.
8. Allen: Let's try... [making a new waypoint, E1 to E3]
9. [As he runs the model, E3 moves forward and backward from very close view and other planets are also seen from very close positions.]
10. Allen: What in the world?
11. Betty: I think they are running into each other...

A waypoint is a viewpoint defined by observer location and target direction. Learners choose where to "look from" and "look at" as in [8]. Using orbital disks, they realized that the differences among eccentricities values were not significant enough to have noticeable differences in orbits [12-16]. As they changed the values to have bigger differences, they saw the differences in shapes [17-21].

12. Betty: Maybe we should view it with the orbit thing. You know what I am saying?
13. Allen: Oh, ah, good! [going to the menu and turning on orbital disks for planets]
14. [As the orbital disk of each planet is turned on, the shapes of orbits show, which are all close to circles.]
15. Allen: OK, let's do this... actually make the eccentricities further apart.
16. Betty: OK, good call.
17. Allen: 'Cause it can be between 1 and 0, so we got a lot to play with.
18. Betty: And we will be able to see it better.
19. Allen: [modifying E2 ($\epsilon=.1$)] Now, orbital disk... [turning on its orbital disk] Little bit better?
20. Betty: Yeah. [Allen changing the eccentricities of E3 ($\epsilon=.3$) and E4 ($\epsilon=.8$), turning on disks.] (Figure 3)
21. Betty: OK, the closer to zero, the more circular they are.
22. Allen: Yeah, it was zero, not the other way around.



Figure 3. A screen capture from Betty and Allen's 09/08 video: Eccentricity pre-exercise

Here, Betty played a significant role in creating a meaning of eccentricity. She suggested utilizing visual representations of orbits [12-13], which enabled them to see the actual shapes of the orbits. This helped them to understand the eccentricity values [21]. Allen realized the information he provided earlier was incorrect [22].

Development

Through the process of working with new partners, definitional, numeral, and visual meanings of eccentricity started to be associated together in their knowledge structure. Allen played a main role of manipulating

Table 2. Eccentricity pre-exercise

	Betty and Allen	Astronomicon
Knowledge	Eccentricity; Its values and orbit shapes	Underlying physics; Modeling interface; Eccentricity value range; Waypoint interface;
Functions	Decisions about input values/ observation tools (orbital disks)/perspectives; Trial-error approach (inputting/ observing/judging ϵ values)	Rule executions with learner inputs to create planets and create views for waypoints; Simulate motions of planets
Representations	Notes about the task on the board; Data taken from Astronomicon demonstrating differences in eccentricity (similar to Figure 3)	Modeled system with 4 planets; Visualized orbital disks; Waypoint, E1 to E3; Waypoint, Overhead view (Figure 3)

Astronomicon, Betty facilitated their observation, and Astronomicon produced models and visuals with inputs. For this activity they used the most basic problem-solving strategy, which is trial-error approach. This activity allowed learners to take this weak method, with which learners start with no testing hypothesis and make claims based on pure observations of what is produced in Astronomicon with their uninformed inputs. They became familiar with using visual representations (orbital disks) by the exploration of one variable (eccentricity). These comprised their first step toward the development of expertise as summarized in Table 2.

The subsequent four weeks (exercise 1 & 2) prepared Betty and Allen with basic modeling and observation skills and system variable knowledge (e.g., mass, distance, rotation rate, and orbital period). Their understanding of underlying relationships helped them to see the variables' relevance to the current observations. Building a model for exercise 3 (Orbital motion), Allen did bother to input some of the values accurately, such as size and rotation rate. They knew that most of the planets would look as small as dots when observing the orbital motions so that they only needed to focus on the values that would affect orbits, such as eccentricity.

23. Betty: They still look pretty circular.
24. Allen: I am going to actually change them more elliptical [changing Earth's eccentricity to .9]
25. Allen: [pointing to the screen] Look how close it is to the sun. It's actually inside of Mercury and Venus... 'cause it's point nine. [running the model] It's kind of crazy.
26. Betty: [watching the screen] Yeah... crazy.
27. Allen: [Earth moving from the far side of the orbit around the sun] See how slow it goes...
28. Betty: So where is the Earth now?
29. Allen: [selecting Earth and running and accelerating the model] Faster... I just want to see what happens when it gets back closer. It's going to be speeding up here. [pointing to the screen, the closest point of the Earth's orbit to the sun]
30. Allen: [Earth moving much faster closer to the sun] Shook! [stopping and resetting the model] I guess we need to do some waypoints actually.
31. Betty: Yeah. Well, hang on... OK, we are trying to prove that one of these is wrong and one of them is not. Oh, we probably take a picture of the Earth orbit with Mercury highlighted? So... 'cause you could see that that can't be how it really is because Earth would not be inside of Mercury.
32. [Allen nods his head and turns on the orbital disks of the Earth and Mercury.] (Figure 4)

Figure 4. A screen capture for exercise 3 report by Betty and Allen: Eccentric planet orbits (Earth, 0.9; Mercury, 0.3)

Beyond the relationship between the orbital shape and the eccentricity value, they realized the changes in Earth's relationships with other planets and the sun. The first thing they noticed was the changing position of the Earth in relation to Mercury and Venus, which was an important differentiating factor from the real system [25, 31]. Another observation was on the effect that the eccentricity had on the planet's speed of movement [27-30].

Episode Three: Eclipses and Eccentricity

Learners show the qualitative and quantitative changes in their knowledge structure when gaining more competencies in a specific area (Alexander, 2003). When Betty and Allen made the four Earths with different eccentricities during the first episode, they did not know what they would get from that change. During the eclipses exercise (the ninth week from the first episode), however, Betty and Allen made changes to the parameters with certain expectations about the results because they became able to deduce possible effects or no effects on the phenomena. They brainstormed the changes they could make, disregarded the ones that would not affect the phenomena, and tested the ones that they expected to cause some changes. In the following episode they were about to reason about eccentricity as one of the variables for the frequency of solar eclipses [36].

33. Allen: If we change... how much the moon goes around the Earth, it might change...
34. Betty: OK...Rotation rate? No, that's rotation around the axis, isn't it? Oh, could we change the eccentricity to be smaller?
35. Allen: I don't know what that would do.
36. Betty: No, it wouldn't 'cause it is already almost circular. Or we could make the eccentricity bigger.
37. Allen: More elliptical?
38. Betty: It would reduce the number of eclipses, wouldn't it?
39. Allen: Do you want to make it really eccentric? [opening the Moon edit window]
40. Betty: Yeah, like point seven.
41. Allen: [putting in .7 and running the model from the moon to Earth view] Let's look and see what happens at 121.
42. [The timer count passes day 121 and they do not see any shadow going by.]
43. Allen: [stopping the model] No eclipse. So do you want to take a picture here when we do not have one?
44. Betty: I don't know. Let's wait until we see the first one. It might never happen.
45. Allen: Well, that's part of the question too.

They decided that a more elliptical orbit would change the frequency of solar eclipses and started making observations [36-41]. They checked the day (about 121 days) when they had the first solar eclipse in the real system [41-43]. They found that a more elliptical orbit would take a lot longer to have sun, moon, and Earth in line. Figure 5 is the image used in the lab report of Betty and Allen, which demonstrates the Earth and the moon were in line with the sun using orbital disks.



Figure 5. A screen capture from Betty and Allen's exercise 5: The moon ($\epsilon=.7$) in line between the Earth and the sun

Table 4. Eclipses of planets with eccentric orbits

	Betty and Allen	Astronomicon
Knowledge	Eccentricity; eclipses; planetary motion and light; relationships among planets (alignment)	Modeling interface; waypoint interface; relationships among time, planetary motions, and light
Functions	Decisions about input values/observation tools (orbital disks)/perspectives; abstract deduction; time-relevant pattern observation	Rule executions with learner inputs to create planets and create views for waypoints; timed motions of planets
Representations	Data taken from Astronomicon to show the rare alignment they encountered (Figure 5); data taken from Astronomicon to show the Moon shadow cast on the Earth	Modeled sun-Earth-moon system with highly elliptical orbit of the moon; visualized orbital disks; waypoint, overhead view of the Earth (Figure 5); light effects; timer (day counts)

Development

In this episode Betty and Allen associated another aspect (eclipses) to their knowledge of eccentricity. As emphasized in Table 4, they were utilizing Astronomicon's embedded knowledge about time, planetary motions, and light in order to understand eclipses' frequencies. They observed the patterns of the phenomenon as well as when things happened. As their problem-solving strategies, Betty and Allen deduced what would happen when changing certain variables without actually trying it out [33-38]. This indicates their developed understanding about inner workings of solar system. In their reports for this exercise, they used multiple image data taken from various perspectives in Astronomicon in order to show 1) the shape of the moon's orbit and its alignment, 2) the eclipse occurring seen from the Earth, and 3) the eclipse trail on the Earth, seen from the moon. This shows the culmination between Astronomicon's capabilities to represent modeled system from various perspectives and the learners' abilities to utilize the representations to support their claims and demonstrate their understanding.

Episode Four: Seasons and Eccentricity

Betty and Allen developed their knowledge structure about the solar system and various factors regarding its inner workings throughout the semester. Through the last exercise (seasons), they added another dimension (temperature/luminosity) to their understanding. They explored how the change in eccentricity affected seasons on a planet due to the variations on the orbit's speed and distance. Betty and Allen were able to abstractly reason through the model's operation based on their knowledge of inner workings. In the following episode they brainstormed to model an alternative theory of Earth's seasons: *seasons are influenced by the Earth's changing*

speed in its orbit. Allen opened the edit window of the Earth (Figure 2) to think of different parameters to change [46-47]. He considered eccentricity because they had seen the speed variations from previous exercises [47-49].

46. Betty: Alright, how do you change the speed of the orbit?

47. [Allen selects the Earth, opens its edit window, and clicks on the eccentricity box.]

48. Betty: Now how would that change?

49. Allen: You see,... it has an average speed, but remember when it's really elliptical, it slows down when it gets away from gravity, and it gets faster as it goes close by it. [drawing an orbit with an index finger]

50. Betty: Right... now that would change it because that would make it go farther away from the sun?

After changing the eccentricity of the Earth from .02 to .7 and attaching an orbital path (Figure 6), they talked about other factors [51-53]:

51. Allen: OK, in order for it not to be affected by anything else but speed...

52. Betty: No tilt.

53. Allen: No spinning.

54. Allen: [changing the rotation rate from 1 day to 365 days] If it spins once every 365 days, then the same side is facing the sun 'cause it goes around in 365 days. [lifting his right hand as if holding a ball up; moving it from right to left and rotating it counterclockwise at the same time] Now, the same side is facing the sun... that means the other side won't get any...

55. Betty: Sun?

56. Allen: Right... so I don't think that would work.

57. Betty: Yeah, change it back to normal. [Allen changes it back to 1 day]

58. Allen: [watching the screen] With that elliptical orbit, I think it will still be the same. (see, Figure 6)

59. Betty: You mean, seasons?

60. Allen: I mean the tilt... if the Earth is that close to the sun [pointing to the right part of the orbit], it will still burn up, and here it will be super cold [pointing left, away from the sun].

61. Betty: So, the summer will be much shorter than the winter.

Allen thought about the rotation of the Earth as a factor. Without observing the model, however, he was able to dispel that idea by reasoning through it using his hand as a representation [54-57]. As Betty had the knowledge that the tilt affects the seasons on Earth, she considered it to be the main factor [52]. They finally came to realize that the tilt should no longer matter in a different condition (extremely elliptical orbit) [58-61].

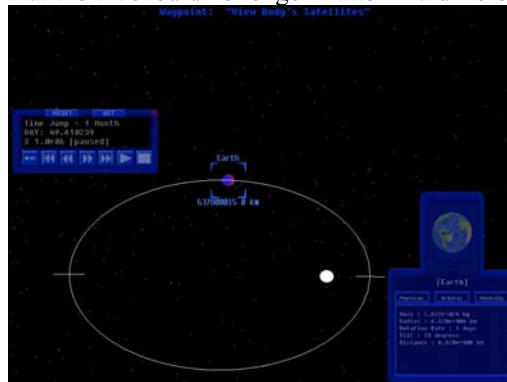


Figure 6. A screen capture from Betty and Allen's exercise 6 reports: The Earth ($\epsilon=.7$) with its luminosity pattern and orbital path

Table 5. Seasons of planets with eccentric orbits

	Betty and Allen	Astronomicon
Knowledge	Eccentricity; changing speed on an orbit; <i>cause of seasons</i> ; <i>tilt of the Earth</i> ; <i>changing distance to the sun</i> ; <i>lengths of seasons</i>	Modeling interface; relationships among time, planetary motions, and light; <i>luminosity</i>
Functions	Decisions about input values/ observation tools (<i>orbital paths</i> , <i>pattern visualization</i>) /perspectives; abstract deduction; time-relevant pattern observation	Rule executions with learner inputs to create planets and create views for waypoints; timed motions of planets
Representations	Data taken from Astronomicon demonstrating differences in eccentricity (Figure 6); <i>Hands</i>	Modeled sun-Earth system with a highly elliptical orbit; <i>visualized Earth's orbital path</i> ; <i>luminosity pattern visualization</i> ; waypoint, overhead view (Figure 6); timer (day count)

Development

We can infer that the intellectual partnerships of Betty and Allen with Astronomicon had changed throughout the semester. They were less dependent on pure observations for their reasoning and more dependent on the knowledge structure that they gained by working with Astronomicon. Betty and Allen approached their tasks through a different kind of thinking; they were asking, "What value can we change to make a certain thing happen?" instead of "What happens if we change this value to something else?" For the former they needed to know the underlying principles, but not for the latter. This kind of abstract reasoning is possible only when learners have the coherent knowledge. Emphasized in Table 5, eccentricity became a relevant concept with tilt, distance, and speed in relation to cause and lengths of seasons. During this time Betty and Allen chose to use orbital path instead of orbital disk in order to see better and did not bother to add texture for the sun (Figure 6). This indicates that they were now focused on using representations in support of their inquiry.

FACILITATING THE DEVELOPMENT OF JOINT LEARNING SYSTEMS

The above account illustrated the process of a group's gaining expertise and developing the partnership as a joint learning system. The complex process of their development was reconstructed and exemplified with the concept of eccentricity with four episodes. Overall, Betty and Allen started the semester as novices in their skills for inquiry and the tool with some differences in their interest and knowledge levels. As a team, they gradually gained expertise in modeling-based inquiry, and clearer knowledge and mental models about the solar system.

From the perspective of expertise theory, Betty and Allen showed their progress in their knowledge structure, problem-solving strategies, and automaticity (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996). Through

investigating phenomena by building and testing models each week, they associated the underlying principles of the solar system with their understanding of the Astronomicon models' inner-workings (knowledge structure). Their inquiry strategies moved from trial-error approaches toward more focused inquiries of making predictions and devising Astronomicon features to understand relationships (problem-solving strategies). They gradually found their roles in this team and internalized their inquiry process as well as the procedure of building and observing models (automaticity). As exemplified in the episodes, the gains from each week became important foundations for their performance in the following week, making their partnership stronger little by little.

The changing pattern of knowledge structures for Betty and Allen was consistent with the changes indicated in expertise literature moving from a more fragmented knowledge to a more cohesive and deeper one (Alexander, 2003). Betty and Allen's knowledge about astronomy was initially based on their common sense and some bits from their former science classes. They were dependent on the Astronomicon interface to know the needed input variables without understanding what each value meant for the model. They gradually gained a better knowledge structure of the solar system and learned how some of the values related to model properties such as eccentricity to orbital shape. The way they worked with Astronomicon and conversed during the class indicated cohesiveness in their knowledge structure. They often recalled some values that were frequently used and differentiated some of the factors that would not affect their current modeling and observations from the relevant ones.

They came to better understand the fundamental relationships among underlying factors and their effects on the patterns of planetary light and motion. Their knowledge was constructed in a situated manner; that is, it was used, tested, and visualized within their modeling activities. They broadened the observer's viewpoints as they investigated from one planet to another and even from (or to) specific spots on a planet. Betty and Allen's improvement as novice scientists can be also noticed from their maturity of writing their lab reports, which moved from demonstrating their creation of model to making evidence-based claims with collected image data from Astronomicon. In their posttests Betty made 29 percent of improvement (67 percent of correct answers) and Allen made 20 percent of improvement (73 percent correct).

Through Betty and Allen we saw a joint learning system in action, partnering and evolving. The designed curriculum had supported the process of gaining expertise in modeling-based inquiry for basic astronomy. Both learners became confident in and good at their tasks and roles, and their report grades started as average and reached perfect points. Betty and Allen, however, had multiple challenges, had some concepts never completely clarified, and had inquiry strategies not fully internalized. Betty and Allen, unfortunately, did not expand their understanding about the solar system much beyond the sun-Earth-moon system. For their last activity in exercise 6, seasons, they first experienced how Venus would be different from what they had been modeling and observing mainly with the Earth and the moon. Their standard conceptions of time, such as day and night, seasons, and year, were completely overthrown by making the factual numbers of Venus take action in Astronomicon. However, this activity became the very last one that they briefly encountered. Astronomicon was designed in a way that allows a learner to expand his or her perspective centered on the solar system, and such activity could be easily incorporated with any current tasks.

The baseline activities need to be more focused and expanded in order for learners to have fundamental understandings of underlying relationships, not just within our sun-Earth-moon system, but beyond. Focused activities, such as investigating the factors that affect the lengths of a day—not only for Earth's day, but also for days of other planets, would engage learners in exploring with their models and have an experienced and solid knowledge structure. Another challenge that needs to be addressed is learners' lack of engagement in the scientific discourse using right terms and theoretical underpinnings. In addition to making connections among various phenomena with eccentricity, some theoretical discourse including, aphelion/perihelion, Kepler's third law, and foci of elliptical orbits, should be more tightly embedded within their inquiry activities.

CONCLUSION

Through this study, we have gained a deeper understanding of the process whereby a pair of learners develops their intellectual partnership with a cognitive tool for scientific inquiry. We found that all the successes as well as the challenges that they had were interrelated throughout the semester and that each success or challenge has its own individual history. In order to better facilitate cognitive partnerships, the tool and the activities should support gaining expertise on the aforementioned aspects. In other words, the tool should be designed in a way such that its capabilities are apparent, not hidden to the learners, and the activities should support mastering those features in addition to addressing important concepts. Why the learners interact in a particular way could not have been explained without considering learners' histories, because every action they took was the consequence of their prior interactions with the tool and with each other (Hutchins, 1995). The future research on intellectual partnerships of joint learning systems should be expanded to comparing groups with distinctive characteristics, as different learners will form different joint relationships.

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