RETHINKING COGNITIVE TOOL:
ITS CONCEPT, DESIGN, APPLICATION, AND RESEARCH
by
BEAUMIE KIM
(Under the Direction of Kenneth E. Hay)
ABSTRACT
Previous research and development with cognitive tools has been limited by an inadequate conceptualization of the complexity underlying their nature and affordances for supporting learning and performance. This dissertation provides a new perspective on cognitive tools through the lens of the theories of distributed cognition and expertise. This enhanced perspective is used to clarify the nature of cognitive tools and distinguishes them from other types of computer tools used in learning contexts. The implications of this new perspective are presented in reference to research, development, and practice.

The first focus of this research was the design issues of a cognitive tool by examining and comparing interactions across different groups of learners engaged in common activities. The main purpose was to examine the roles of a cognitive tool and learners, and the functions of specific pedagogical approach in their tool use, in order to improve the designs of the collective learning system including learner, cognitive tool, and learning activity. This study provided important implications for the future design efforts to adopt advanced cognitive tools for learning.

The second focus was on the longitudinal application of a cognitive tool by observing one group of learners interacting with it over an entire semester. The purpose was to develop a deeper understanding of the process whereby learners become more capable of engaging in scientific inquiry with a computer tool. A second purpose of this study was to improve the practice in adopting cognitive tool-enhanced inquiry-based approaches. This study provided insights on what enhances or hinders the development of cognitive partnerships and how to better facilitate the partnering process.
Finally, this dissertation explored how we could examine learner-technology-activity interactions as we study learners, their characteristics, learning process, and learning outcomes without isolating one from another. The discussion was based on the reflection on the research approaches for the two such studies. It intended to describe the theoretical assumptions and questions in the research on cognitive tools, to explain methodological assumptions based on them, to present the case of the research studies in answering the questions, and to provide directions for future research and practice.

INDEX WORDS: cognitive tool, distributed cognition, expertise, inquiry-based learning, modeling, video-based research
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Rethinking Cognitive Tool: Its Concept, Design, Application and Research

The problems of how people view, develop, use, and study computers for education have been mainly due to our tendency of thinking about computers within the framework of what is established. The idea of substituting computers for teachers, textbooks, or television is still prominent. Thinking outside of these conventions, some research and development efforts are now focused on computers that can be tools for learners to solve problems. Some researchers suggest using computers as cognitive tools that learners can think with during their learning (Jonassen & Reeves, 1996). The term, “cognitive tool” is widely used in a more conceptual sense in other fields as one’s mind, symbols, language or knowledge. In this work cognitive tools are tangible objects that learners use in partnership as they are learning.

This notion of cognitive tool has emerged and has been a topic of research over the last decade; nonetheless, its conception still remains abstract and its frame of research does not differentiate itself from other kinds of educational research. Rethinking of cognitive tool, therefore, is a necessary effort of finding the meaning of cognitive tools for the design, development, research and practice beyond its abstract conception. This dissertation is a collection of articles aimed focused on the advancement the research and development of cognitive tools, it includes: a conceptual review and framework, two proposed studies, and a methodological review and reflection. The first paper, Reframing Research on Learning with Technology: In Search of the Meaning of Cognitive Tools, provides a conceptual framework for research and development of cognitive tools through an alternative way of conceiving cognitive tools. Built on a foundation of two learning theories and literatures (distributed cognition and expertise), this paper builds a rationale that a cognitive tool is best conceptualized as a cognitive partner with learners. Learners interact with their partner as they construct knowledge, bringing its expertise to activities.
The two study articles, *Creating a Universe with Computer: Charting the Structure of Distribution between Learner and a Cognitive Tool* and *The Evolution of the Intellectual Partnership with a Cognitive Tool in Inquiry-Based Astronomy Laboratory: Icebreaking, Getting Along, and Bonding*, report the actual investigations of the structured conceptions, especially regarding the design and application of cognitive tools: what intellectual partnership between learners and the tool is actually looks like (i.e., what features are used or not used and how they are used for certain cognitive tasks); and how learners’ growing expertise in use of the tool for scientific inquiry impacts their development of intellectual partnership with the tool and how those partnerships evolve over time. The studies were conducted concurrently in the same setting (an undergraduate Astronomy Laboratory) where students, working in pairs, learn through an inquiry-based framework (Modeling-Based Inquiry) and with a particular cognitive tool (Astronomicon) that resemble the tools of a scientist. Their interactions and conversations were recorded with separate video, audio, and computer screen captures, which are simultaneously viewed and analyzed using a web-based analysis system. Any number of separate video for each group and entire class, and audio and computer screen for each student can be selected and viewed on the web-based system to understand specific situations and interactions (e.g., two group videos, four participant audios, and two screen captures to analyze the interactions of two groups comparing their models).

The last paper, *Looking through Multiple Lenses: Reflection on the Methodological Approach in Learner-Technology-Activity Interactions* formally presents the methodology with which cognitive tools can be studied in our field. This paper explores how we can examine learner-technology-activity interactions as we study learners, their characteristics, learning process, and learning outcomes and how we can bring them together without isolating one from each other. The discussion is based on the reflection of the research approaches for the two such studies. It intended to describe the theoretical assumptions and questions in the research on cognitive tools, to explain methodological assumptions based on them, to present the case of the research studies in answering the questions, and to provide directions for future research and practice.
These four papers constituting my dissertation work is at the continuum of my pursuit for research and development interests, which can be summarized into four themes: 1. Learning science through artistic minds, 2. Engaging scientific inquiry with cognitive tools, 3. Conducting research on learning technologies through interaction data, and 4. Integrating innovative educational technology into informal and public education.

1. Learning science through artistic minds

Science is often presented as its discovered facts, the science products. The focus of advanced science on memorization of facts and mathematical formalisms also makes its process look hard and rigid, leaving no room for artistic minds. However, the areas of arts and sciences, I believe, are on the same continuum, as art comes from the appreciation of what we observe and how we feel, whereas science is about understanding those natural phenomena. One of the foci of science learning should be on how we attend to the things happen around us, make representations of our understanding, and make connections with existing representations of those phenomena.

Scientific visualizations and more holistic presentations of mathematical relationships with modern science technology are more attuned to making these connections. I am interested in how advanced technology can support learners in approaching science through the artistic mind and visually representing what they learn. Following the pedagogical approaches of art education and constructionism, learning becomes active and meaningful experience by producing something meaningful for the learners.

2. Engaging scientific inquiry with cognitive tools

A relevant interest area is the research and development of cognitive tools using emerging technology and appropriate learning theories. Particularly, I am interested in the scientific inquiry tools that can be used in constructivists’ learning environments where learners use them for authentic activities and construct their understanding, not for sources of information. When we design these tools we should consider how it will actually be used in learning situations, as to how the roles of learners and tools play out in carrying out learning activities.
Science learning, therefore, should be experiencing science, which is the investigation process of scientists. Technological advances have created new roles of modeling and visualizations in modern scientific investigations. Many scientists no longer study phenomena, say, by looking at the sky, but by looking at the models and visualizations. As researchers in the field of instructional technology, we live in a very exciting era, in which advanced visualization technology is being transformed into a much more accessible format whereas most of data visualizations could only be accessible through special computers that were not available to the public. These modern means of scientific inquiry can now be applied for educational purposes as traditional science laboratory materials were.

3. Conducting research on learning technologies through interaction data

The methods of educational research that involves technology can vary a great deal depending on the purpose of research. I am mainly concerned with methodologies with which we can examine better about learners’ interaction with the technology, which is the scientific thinking process that intends to be similar to that of scientists. The researcher herself is the most important research instrument as the understandings about the tools and the processes can be done only through the observations of and discussions with the scientists and the learners.

The researcher, however, has limited ability to see, hear, and record the complex event of this kind of learning experience. One of the most helpful instruments for capturing interactions between learners and the computer is the video devices, including screen captures and learner voices. I have been working with video-based research for computer-enhanced inquiry-based science lab, and seen the benefits of using videos for in-depth understanding of learning interactions. It was not until I started watching the video captured events that I realized how little had I understood about their experience by observing them in class. I felt as if I was finally involved in their learning experiences more so than when I was in the classroom. Participating in and observing the experiences of learners using the tools can be augmented by using video devices.

4. Integrating innovative educational technology into informal and public education
The ultimate measure of a successful research and development project is its impact on our education. New approaches, especially those using emerging technologies, tend to reach a small number of learners due to the constraints of curriculum standards, lack of resources, and so forth. For this matter, I would like to explore the ways to promote the public awareness of the promising approaches and technology, such as inquiry-based learning and 3D modeling technology, beyond research community because conscious public including parents and educators also give direct impact on the trends and movements of education. Some ways to reach the larger public include documenting and reporting the practices of new approaches through mass media, developing learning programs for informal education spaces, and providing professional development programs for educators. I am particularly intrigued by the settings that are somewhat informal, such as labs and after school programs, or completely informal, such as museum and science center educations, where learners can have opportunities to experience innovative learning approaches through authentic activities more freely than formal education settings.
CHAPTER 1

REFRAMING RESEARCH ON LEARNING WITH TECHNOLOGY:

IN SEARCH OF THE MEANING OF COGNITIVE TOOLS¹

¹ Kim, B. & Reeves, T. C. To be submitted to Instructional Science
Abstract

Previous research and development with cognitive tools has been limited by an inadequate conceptualization of the complexity underlying their nature and affordances for supporting learning and performance. This paper provides a new perspective on cognitive tools through the lens of the theories of distributed cognition and expertise. This enhanced perspective is used to clarify the nature of cognitive tools and distinguish them from other types of computer tools used in learning contexts. The implications of this new perspective are presented in reference to research, development, and practice.
Reframing Research on Learning with Technology: In Search of the Meaning of Cognitive Tools

In the past, proponents of educational technology have argued that there simply were not enough computers, software, or support in classroom to have significant impact on educational outcomes. Over the last decade, however, the ratio of students to computers has steadily improved, increasingly powerful software packages have become widely available, and assistance for teachers and faculty has been increased through the introduction of technology coordinators in K-12 schools and additional technology support personnel on college and university campuses (Becker, 2000; Pittinsky, 2003). Despite enormous increases in technological infrastructure and support, it still remains difficult to find evidence of significant impact of computers on teaching and learning at any level of education. (Cuban, 2001).

Many of the problems with how people view, develop, use, and study computers in education stem from thinking about computers within the framework of long-established mainstream educational practices. As described in Jonassen and Reeves (1996), much of the disappointing results of the application of computers in education can be attributed to a misguided emphasis on using technology as something that students should learn “from” in a fashion similar to how they might learn “from” classroom teachers, textbooks, or television. Although the conceptualization of using computers as tutor, tool, and tutee was proposed a quarter century ago (Taylor, 1980), researchers and practitioners have only recently attempted to employ computers as “cognitive tools” for learners to learn “with” while they are solving problems or completing tasks (Lajoie, 2000a; Lajoie & Derry, 1993). Unfortunately, immature use of computer as cognitive tools has also led to disappointing results. Instead of using computers as tools to learn “with,” teachers focused on helping their students to master the tools themselves. (Oppenheimer, 1997) criticized this approach with an analogy of schools trying to teach “hammer” instead of “carpentry.”

Cognitive Tools to Date

The scholarship of cognitive tools is founded on constructivist beliefs about how learning occurs and how learning environments should be designed accordingly. Although complex and rife with controversy (Phillips, 2000), constructivism in education can be boiled down to the concept that learners
actively construct their own knowledge rather than passively receive it (von Glasersfeld, 1995).

Constructivist learning requires constructing our meanings through reflection and continuously reconsidering our existing interpretations of the world (Salomon & Almog, 1998).

The results of the cognitive activities of learners should be the consequences of constructing knowledge “with” computer tools rather than learning “from” computer tutorials in a manner previously structured by someone else. The focus on the use of computer tools for cognitive activities for learners to think “with” is derived from the theory of distributed cognition (Salomon, 1993c). Distributed cognition implies that learners are enabled to think deeply and create certain types of artifacts that represent their thinking by working with cognitive tools.

In general, physical tools are utilized to enhance the performances of human activities (e.g., digging a hole in the ground) or to do tasks otherwise impossible (e.g., examining cell structures of fruit flies). Tools for cognitive activities are comparable to the physical tools that are invented for everyday human activities in that they change and enhance our way of doing mental activities, create new ones, and are steadily improved as they are adopted and used by more and more people. A good example of the development, effects, and refinement of cognitive tools is the way that mathematical symbols have evolved throughout history.

The conceptualization of computers as cognitive tools has been refined and the development of actual cognitive tools has progressed greatly in recent years (Nickerson, 1993). Unfortunately, researchers have used different names to signify the application of computers to advanced mental activities, such as cognitive technologies, technologies of the mind, cognitive tools, and mindtools (Jonassen & Reeves, 1996). Salomon, Perkins, and Globerson (1991) describe computers as “partners in cognition” that extend human cognitive capabilities. Given the abstractness of the term, it is hardly surprising that researchers and theorists proposing these new ideas about cognitive tools have expressed diverse views (Jonassen, 1996; Lajoie, 1993; Salomon, 1993a).

These different labels share similar connotations with both physical tools (e.g., hammer) and intangible mental tools (e.g., symbols) in that they help by enhancing or extending human capabilities
(e.g., Falbel, 1991; Jonassen, 1996; Lajoie, 1993; Salomon, 1993b; Salomon, 1991). At the simplest level, cognitive tools can be defined as aides for cognitive tasks such as complex calculations (Lajoie, 1993). With more elaboration, Jonassen and Reeves (1996) characterized cognitive tools as “technologies that enhance the cognitive powers of human beings during thinking, problem solving, and learning” (p.693). By enhancement, they meant that people can have deeper, more reflective thoughts by distributing mundane tasks to the tools (e.g., calculations), or are able to perform cognitive tasks impossible without such tools (e.g., modeling complex interactions) (Jonassen & Reeves, 1996).

Salomon (1993a) added more conditions to explain cognitive tools by suggesting that they are open-ended instruments that students operate and manipulate to help themselves engage in constructive thinking, allowing them to think beyond their cognitive limitations. The “open-endedness” is important in Salomon’s definition because it signifies that students are the ones who actively make decisions about their mental processes and the need for cognitive support.

Issues for Cognitive Tools Research

The movement to use computers as cognitive tools or partners in education over the last decade has not progressed to the degree that has long been desired by advocates such as Lajoie (1993), Jonassen (1996), Papert (1993), Salomon (1993c), and others. Perhaps cognitive tools researchers should be more mindful and reflective in defining what makes a computer program a cognitive tool. One prominent issue is whether the nature or the use of a tool makes it a cognitive tool. Lajoie and Derry (1993a) introduced cognitive tool initiatives that basically have three different natures: modelers of learners’ thinking, non-modelers, and initiatives that combine the two. Others have discussed computer tools as specially designed cognitive “partners” (Salomon, 1993b). By contrast, Jonassen and Reeves (1996) focused their discussion on the use of everyday computer programs such as spreadsheets and databases as cognitive tools that learners’ employ for knowledge construction.

There are other issues that contribute to the fading conversations about cognitive tools. The notion of cognitive tools has been explored by many scholars, but still remains somewhat abstract, thus
limiting the progress of its research and development. Not only is the main concept of cognitive tools ambiguous, but also are its associated ideas for research and practice:

1. the lack of understanding about the design and values of cognitive tools;
2. too brief and/or inappropriate adoptions of the tools in the classrooms; and
3. the disintegrated research approaches that do not feedback into the advancement of the fundamental ideas.

The Lack of Understanding of Design and Values

Even the simplest invention, such as plastic cups, has benefits and losses, e.g., consumer convenience and environmental pollution. Cognitive tools also have their trade-offs of which we must be mindful (Pea, 1993). Many people have come to rely on email communications, and yet at the same time, some miss the intimacy of hand-written letters. The activities inherent in writing a traditional letter, such as choosing a good stationary and a fine pen, presenting content within the guidelines of certain formats, writing addresses, and attaching stamps, are either transformed or completely lost in an electronic format. With respect to using cognitive tools in education, we should think about whether we are providing cognitive tools that transform learners’ cognitive activities toward higher-level thinking, or providing them with future disabilities by requiring the use of cognitive tools in the formal learning environment, but expecting learners to do without them outside of schools. For example, according to a recent report (Levin & Arafeh, 2002), some middle and high school students have become so reliant on the Internet as a source for educational content and instruction that they have come to view traditional media (e.g., textbooks) and even their teachers as irrelevant.

Falbel (1991) addresses another design issue by seeing a tool by itself as both value-neutral and value-laden. Tools embody certain values imposed by their design, but they are value-neutral until used in certain ways by particular learners (Falbel, 1991). The choices that learners make to use cognitive tools can be more open or limited depending on the nature of the tools and the design of the learning environment in which they are to be employed. Educators should be aware of both the value that cognitive tools bring to the fore in any educational context as well as the possibilities they open up for the
learners. Cognitive tools can be developed with elaborate features intended for higher-level learning and thinking, but problem arise when the value of them are not seen by the learners nor not reflected in learning activities. Although some studies report successes in using cognitive tools in class, such studies report that learners were often unable to use the various features of tools to go beyond modest expectations (e.g., Brown et al., 1993; Edelson, Gordin, & Pea, 1999; Spitulnik, Krajcik, & Soloway, 1999).

The Brief and/or Inappropriate Adoptions

The assumption that learners will automatically take appropriate and measured advantage of the affordances of computer tools when involved in cognitive activities with them is dubious (Perkins, 1993; Salomon, 1993a). For cognitive tools to actually become an extension of human cognition, students must strive to engage in activities mindfully. Cognitive tools are not like films that automatically generate movement and sound to gain passive attention from people; they require deliberate attention and effort from learners to make them do something. Activities requiring cognitive tools are not as effortless as watching a multimedia presentation, but as vigorous as creating one. Learners should be mindful and reflective in working with cognitive tools, constructing their knowledge and its representations (Norman, 1993).

We should carefully study the transactions that learners make when they interact with cognitive tools and develop their cognitive partnerships because cognitive tools are intended to leave the decision-making and higher-order thinking on the part of the learners, not to provide them with instruments that allow them to accomplish tasks and solve problems mindlessly. For example, students using statistical analysis packages as cognitive tools sometimes mindlessly accept results that are preposterous.

Another issue facing researchers focused on educational applications of cognitive tools is communicating their ideas of cognitive tools to practitioners and ensuring that these tools are used appropriately in the classroom. Salomon and Almog (Salomon & Almog, 1998) argued that no matter how we try to transform the way students learn in classroom with new technologies, the established classroom structure usually undermines the intended use of the tools (e.g., instead of using a tool such as
CAD/CAM software for complex tasks, students are taught one way of using the tool step-by-step to accomplish routine tasks). Admittedly, the ill-structured nature of activities using cognitive tools sometimes makes it harder to manage classrooms and evaluate student performances, thus making appropriate use of them more difficult (Resnick & Ocko, 1991).

The Disintegrated Research Approaches

Significant research and development have been done under the broad umbrella of cognitive tools in the last decade with various research approaches. Studies of cognitive tools vary widely in the sorts of tools used, e.g., simulation of medical experts’ activities (Lajoie, 1993) and employment of scientific visualization tools (Schwartz et al., 2000). Using various research methods, such as tests, observations, interviews, and think-aloud protocols, researchers have attempted to find what significance these tools have in student learning. Contemporary learning theories extend the property of knowledge and performance outside an individual’s mind (Brown et al., 1993). Many of the studies on computers in education, however, still focus on technology and learner performances separately with minimal attempts to capture their interrelationships.

Researchers have confronted similar issues in ways that may have limited progress in the development, research and application of cognitive tools. Erkunt (1998), in reporting his study about a cognitive tool, concluded that the concept of cognitive tool is useful but vague, thus making its empirical research difficult to describe. The research approaches applied to it have not been sufficiently differentiated from other kinds of educational research. Computer applications designed or adopted as cognitive tools have been investigated in terms of what learners were able to accomplish during and/or after learning with the tools. However, the relationships between learners and tools, i.e., their roles as intellectual partners and partnering processes, were not adequately addressed in most research studies. It is hard to capture the partnering process within a short period of usage time and often not possible to observe and report the process with conventional research approaches. As a result, the principles of using computers as cognitive tools have not been realized at any level of education. New researchers in
cognitive tools who wish to contribute to their development and application, thus, should adopt research methods that can take complex interrelationships into account.

A Need for an Integrated Framework

There is a clear need to define an integrated framework for the study and practice of cognitive tools. This framework should be conceptually coherent to foster more successful design, application, and research. Such a framework would allow designers and researchers to specify what features of tools are used or not used and how they are used for certain cognitive tasks. The practical issues of cognitive tools would then come down to developing appropriate learning activities for higher level cognitive tasks, so that the tools are used in ways that neither give learners easy answers nor frustrate them with complicated features. Learners could be challenged with authentic tasks, wherein cognitive tools are actually needed to accomplish them.

In light of this need, the primary purposes of this paper in sum are:

1. to critically review and identify the potential benefits and weaknesses of the previous research and development of cognitive tools;
2. to propose an integrated framework for research and development;
3. to redefine cognitive tools and examine renowned learning technologies with the alternative framework;
4. and to prescribe an agenda for research and development to maximize benefits and overcome weaknesses.

In short, we intend to develop the meaning of the cognitive tool beyond its abstract conception, in order to support the more widespread research and practice of computers as cognitive tools. This paper first describes two underlying learning theories (distributed cognition and expertise), presents the new framework, and then explores the potential for advancing cognitive tools based on this new perspective.

Conceptual Background of Cognitive Tools

Inquiries into how learners construct their knowledge require as much attention to learning processes as to learning outcomes. Theories concerning human knowledge and cognition, such as
constructivism and distributed cognition have been adopted by many researchers investigating cognitive tools in education. The theory of distributed cognition provides insights into how learners use their environment and its sub-components as integral parts of any learning process (Salomon, 1993c). Distributed cognition is a view that cognition does not reside only in one’s mind, but that cognition is distributed among people, artifacts and symbols during thinking, reflection, and learning (Salomon, 1993a).

Distributed cognition has not been conceived and described consistently. Focusing on the social aspects of human thinking, some theorists agree with Vygotsky (1978) that cognition and activity are distributed basically among people but mediated by signs and tools (e.g., Hutchins, 1995; Resnick, Levine, & Teasley, 1991; Wertsch, 1991). On the other hand, others consider that cognition resides not only in persons but also in signs and tools, conveying cultural meanings and history (Lebeau, 1998; Salomon, 1993c).

Another major difference among views on distributed cognition is regarding whether or not the distribution is an absolute characteristic of human thinking. Some suggest that cognitive activity is always distributed in some respects even when carried out by a person in isolation by virtue of the language used (e.g., Cole & Engestrom, 1993; Pea, 1993; Wertsch, 1991). Others recommend making a distinction between individual cognition and distributed cognition (Brown et al., 1993; Perkins, 1993; Salomon, 1993a). Common to these views is the notion that human cognition relates to the environment outside of an individual.

*Kinds of Distribution*

There is some agreement among researchers that there are social, symbolic, and physical (or material) distributions of cognition [Perkins, 1997 #49; Salomon, 1993a #56]. Social distribution of cognition is often exemplified in workplace settings where the dynamics of team thinking and group decision making are critical (e.g., Derry, DuRussel, & O'Donnell, 1998). Symbolically distributed cognition includes signs, symbols, language, and representation that make our everyday thinking possible. Some researchers do not include symbolic distribution in their dimensions because symbols are almost
always embedded in other kinds of cognition (e.g., Karasavvidis, 2002; Pea, 1993; Perkins, 1993). Symbols used for mathematical multiplication problems (i.e., the two numbers, the position of two numbers, the sign × for multiply, and the line drawn underneath the arrangement of these symbols) have their own culturally provided meanings and convey the cognition of the person who designed the problem (Wertsch, 1998). Physical distribution includes everything visible or tangible, ranging from pencil and paper to artificial intelligent machines. A popular example of physical distribution is the use of a calculator or abacus for mathematical tasks.

A cognitive activity usually reflects some aspects of all three cognitive distributions: social, symbolic, and physical. For example, brainstorming for ideas as a team shows social distribution of cognition among people. Drawing a diagram on the board to visualize their discussed ideas reflects their dependence upon the symbolic and physical distribution.

* Distributed Cognition and Cognitive Tools

People working together affect one another’s thinking and behavior according to social structures and norms. Symbolic and physical means affect our thinking in different ways from people. The symbols that we use have the most direct relationship with our internal mental representations. Physical distribution usually involves some change in artifacts as the result of the thinking process (e.g., the position of beads on an abacus) (Vygotsky, 1978). When using physical means and representations for mental processes, they become a part of the interactions and outcomes of thinking (Pea, 1993; Salomon, 1993a). Sometimes, the involvement of novel symbolic and/or physical means in mental process changes the very nature of the activity (Cobb et al., 1991). In this sense, computers for learning enhance or extend our cognitive powers.

This theory is closely related to the way constructivists think about the role of the computer in the process of learning. The computer is no longer perceived as a mere delivery medium, but as a technology that has unique capabilities to complement a learner’s cognition (Kozma, 1991). Salomon et al. (1991) emphasize this cognitive process by making an important distinction between effects “with” and effects “of” technology. Effects “with” technology result in enhanced intellectual performance during the
learning by the physical distribution of cognition to the technology. On the other hand, effects “of”
technology are evidenced by the cognitive “residue” that remains after completing a cognitive task using
technology, (Salomon et al., 1991).

By distribution, it does not mean that a cognitive activity is divided into parts and assigned to the
computer so that learners could think or work less. Rather, distribution implies a dynamic state of
cognition that is extended by the capabilities of the computer. Cognitive tools should not take over
important human thinking such as decision-making, but perform those cognitive tasks that may prevent
learners from engaging in deeper thinking (e.g., doing repetitive calculations when calculation itself is not
the important part of the task) or help learners think outside of box (e.g., making connections between
boiling water and physics rules by using a special software) (Pea, 1993; Salomon, 1993a). By extending
human cognition, cognitive tools change the nature of activities and open possibilities for new activities.
Moreover, they potentially transform our cognitive structure and processes (Salomon & Perkins, 1998).

Tool Affordances

The impact of computers in education rests in defining them as thinking partners that extend
human cognitive capabilities beyond mere delivery media (Salomon, Perkins, and Globerson, 1991). The
theory of distributed cognition provides an agenda as to how cognition should be distributed among
participants of an activity, focusing on the novel opportunities gained by using computers in learning.

Pea (1993, p.51) employed Gibson’s notion of “affordances” as properties of tools that determine
their usage. Affordances in distributed cognition are the possibilities that symbols and artifacts provide in
the distributed relationships. Those affordances always exist, but not all of them can always be used
without the initiation and desire of the person participating in the distribution (Pea, 1993). On the contrary,
we sometimes become so accustomed to being dependent upon some symbols and artifacts (e.g.,
calendars in both symbolic and physical forms) that their roles for our cognitive activities are not even
recognized, attributing the performance only to ourselves (Karasavvidis, 2002; Pea, 1993). Technological
affordances, the kinds of cognitive functions represented (or possible to represent) in the design of a tool,
are intended to support certain tasks through the designers’ reasoning and decisions, reflecting social
norms and cultural meanings (Karasavvidis, 2002; Pea, 1993). Ultimately, how the technology is used depends on both the intentions of the designers and the users (Moore & Rocklin, 1998).

In summary, the theoretical assumptions about cognitive tools based from the distributed cognition view are:

1. Cognition is distributed between learner(s) and a cognitive tool;
2. The way in which cognition is distributed is first determined by the intentions of tool designers, i.e., tool affordances; and
3. It can then affected by how the learners decide to use it in specific situations.

Expertise and Technology

The theory of distributed cognition highlights the roles of tools in assisting the cognitive tasks of learners, but ideas about how we should decide what to include as functions of technology, how those functions could work with learners, and how we should study these have not been fully established. The theory of expertise provides another dimension that complements the concept of cognitive tools by clarifying perspectives on the nature of excellent performances. This theory is especially relevant to emerging pedagogical approaches that emphasize organizing learning environments so that they are closer to real-world contexts (e.g., Edelson et al, 1999). Within the field of instructional technology, theories of expertise have been discussed and employed mostly in areas such as intelligent tutoring systems and expert systems wherein computers are used to model expert processes (e.g., Baylor, 1999; Feltovich, Ford, & Hoffman, 1997). The theory of expertise allows us to go beyond simply acknowledging the distributed nature of particular learning system to exploring how that system develops and how we can support and design effective learning systems. Expertise theory is discussed in terms of the components of expertise, how they are developed, and how expertise is defined when technology is involved in order to describe and interpret the relationship between cognitive tools and learners.

Expertise is sometimes characterized as a standard of an expert performance in a certain domain (Ericsson & Smith, 1991), or as a relative degree of excellence for a given activity (Salthouse, 1991). Most research studies have focused on expert performances in professional domains, and tried to find the
relatively stable characteristics of experts in performing outstanding behaviors (Ericsson & Smith, 1991). A broader view of expertise, more applicable to the discussion here, contends that everybody has some degree of expertise with respect to our everyday activities (e.g., Brown et al., 1993; Carlson, 1997; Sloboda, 1991).

Assuming a mastery level of performances, conventional expertise approaches attempt to describe the characteristics of domain-specific competences (Ericsson & Smith, 1991; Glaser, 1996). Researchers examine the knowledge structure and cognitive processing of experts during task performance and compare them to those of novices (see Olson & Biolsi, 1991) for detailed analysis process of expert knowledge. More recently, on researchers have recognized the importance of developmental conditions and continuous improvements of expertise and started investigating processes of skill acquisition with exhaustive approaches, such as analyzing the life histories of virtuosos to find general patterns of development (Ericsson & Smith, 1991; Glaser, 1996). Although the theory of expertise is still incomplete, especially in its explanation of early phases of skill acquisition as well as acquisition of mediating mechanisms (Ericsson, 1996), several decades of research have pioneered a refined comprehensive understanding about the nature of expertise: its kinds, structures, and development.

Kinds of Expertise

Experts usually use several kinds of expertise in performing tasks; different kinds of expertise interact with each other and contribute to the process of task performances. Most commonly, distinctions are made between domain expertise and general expertise. Domain expertise is more specific to the knowledge and processing strategies of a certain domain (such as medicine) whereas general expertise (such as creativity) can be transferred and used across different domains. After decades of debate about which expertise is more important in actual performances, it is concluded that they function interdependently in close relationships (Perkins & Salomon, 1989). Schunn and Anderson’s (Schunn & Anderson, 1999, 2001) studies show that expertise in scientific reasoning transferred to other scientific domains. Certain domain expertise, such as literate expertise, often relates with other domains of expertise and affects the performance of tasks (Holyoak, 1991; Scardamalia & Bereiter, 1991). Patel and
Groen (1991) further specified the kinds of expertise as threefold in nature which they labeled generic expertise, specific expertise, and domain-independent (or general) expertise. They classified domain expertise into two categories (generic and specific) in relation to the specificity of knowledge and skills within a domain. As there is more and more specialization within a domain of expertise, a person may possess only generic expertise of the domain, or both generic and specific expertise (Ericsson & Charness, 1994; Patel & Groen, 1991).

**Structure of Expertise**

In the performance of tasks within a domain, there seems to be some structure that characterizes expertise. The elements of structure can be summarized as knowledge, function, and representation, which interact with each other during task performances. The nature and the purpose of knowledge in a field affect how knowledge is organized and processed for effective performances (Anzai, 1991). The knowledge that experts process during practices ranges from more deductive knowledge (e.g., rules and formulas) to more inductive knowledge (e.g., information about exemplars) (Patel & Groen, 1991). When acquired knowledge is organized in a coherent way (i.e., internal representation of knowledge), the cognitive functions, such as recognizing structures or patterns and making inferences, are made easier (Glaser, 1996; Winn & Snyder, 1996). Some of the functions, such as anticipating results and evaluating performance, not only mediate performance but also promote improvement (Ericsson, 1996; Ericsson & Charness, 1994). The ability to use external representations of knowledge and processes also plays an important role in the performances of many domains (e.g., Anzai, 1991). Experts generate complex representations about the 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). Knowledge, function, and representation work together with significant roles in the performance of experts and their development of expertise.

**Development of expertise**

To develop expertise, one must face the problems that challenge one’s current level of knowledge and competences. Not only to develop expertise and become an expert but also to remain an expert, one
should extend the competence level (Scardamalia & Bereiter, 1991). The time a person spends in a field is very important in the development of expertise, although mere exposure should be differentiated from learning and practice (Ericsson & Smith, 1991). The results of studies show that intensive training had much more significant effect on accuracy in clinical judgment than extended experience (Camerer & Johnson, 1991). Development of expertise thus requires a long period of active learning with deliberate practice and learning strategies (Ericsson & Charness, 1994; Ericsson et al., 1993; Perkins & Salomon, 1989).

Understanding how learning activities change over the development of expertise provides an important foundation for education (Glaser, 1996). Research indicates that learners go through the process of gaining knowledge structure, problem-solving strategies, and automaticity during the development of expertise (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996). In structuring their knowledge, novices first make cognitive efforts to understand the task and find important information, and then organize their knowledge into a more accessible structure (Schneider, 1993). This internal structure of knowledge is often revealed and enhanced by their use of external representations, which is one of the most important skills in many domains of expertise (Patel & Groen, 1991). They then learn to use these representations more efficiently with relevant information in a problem (Patel & Groen, 1991).

Novices approach problems with strategies that are based primarily on concrete information, and then they use more and more abstract reasoning as they gain more expertise. Novices rely on the surface features of the problem, commonsense knowledge and trial-error approaches because they do not have enough domain-specific knowledge base and expertise (Anzai, 1991; Patel & Groen, 1991). Gaining more expertise, the person starts to use what is called a general or weak method. This method uses diagnostic reasoning, data-driven reasoning, observation, and problem reduction instead of starting with underlying principles (Anzai, 1991; Patel & Groen, 1991). Experts approach problems with a specific (or strong) method. They work on the problems with working hypothesis and rely on the systematic representation of the information in the problem in relation to their domain-specific knowledge structure (Anzai, 1991; Patel & Groen, 1991). Experts select and focus on only important and relevant information in the problem.
and often switch between general methods and specific methods depending on the problem (Anzai, 1991; Patel & Groen, 1991; Scardamalia & Bereiter, 1991). It is almost impossible to make conscious efforts to switch between different levels of knowledge and strategies during the performance of expert level tasks. For many experts, some of these processes are automatized by their repeated performances on different problem-solving tasks, enabling them to use their cognitive resources to deal with the novel aspects of the current problem situation (Schneider, 1993; Winn & Snyder, 1996).

**Expertise, Context and Technology**

In the earliest research studies, expertise was regarded as a separate property from everyday activities; it was researched in isolated laboratory settings to tease out problem solving processes on a set of standardized tasks. Realizing that individual expertise cannot be fully understood without understanding the environment of the individual, expertise researchers began to look at the dynamics of interactions with environments in the development of expertise (e.g., Keating, 1990; Patel, Kaufman, & Magder, 1996; Winn & Snyder, 1996). Today, many domains of expertise these days cannot even be understood without studying the experts’ use of external aids. These external tools often play a significant role in the work of experts even in studies conducted in isolated labs. Anzai (1991), studying physics expertise, examined the subjects’ use of diagrams as external aids and cognitive representations, and the relationship between the use of diagrams and the level of expertise. Physics diagrams worked as catalyses for information recall as well as tools for computational efficiency and inferences (Anzai, 1991). Simulated computer environments are often used in studying the performance of experts to accommodate some real-world complexity to the experimental setting (e.g., Dörner & Schölkopf, 1991).

Recent expertise studies have extended their research to natural contexts (e.g., Dunbar, 1995; Patel, Kaufman, & Magder, 1996). Dunbar (1995), for example, examined complex cognitive process in the real world in his investigation of the cognitive processes in scientific reasoning and discovery, and recognized the importance of using analogies in the social context of science.

Another line of research in expertise involves analyzing expert reasoning and building computational models to perform complex tasks (i.e., artificial intelligence and expert systems). Studies
of expert reasoning structure to make computational models are very similar to studies of experts’
cognitive processes (Patel & Ramoni, 1997). These machines are programmed to recognize patterns and
perform tasks through sets of production rules (Patel & Groen, 1991). Researchers recognize that there is
a standard way of reasoning requiring deliberate and precise efforts that can be completed by machines
without exhaustion or error, but insist that novel and constructive ways of reasoning can only come from
human beings (Dreyfus & Dreyfus, 1986; Hoffman, Feltovich, & Ford, 1997). These researchers
suggested treating machines as having different objectives from us and imposing the roles that are
appropriate for them (Dreyfus, 1992). In this way, experts are not replaced by the computers, but
empowered by them to make better use of their expertise (Dreyfus & Dreyfus, 1986).

Expertise is not only shaped by the dynamic social context and artifacts in the setting but also
redefined by changes in the ways we do things (Feltovich, Spiro, & Coulson, 1997; Patel et al., 1996).
The expertise of physicians from 50 years ago looks very different from the expertise of present day
doctors with advances of medical techniques and technology as well as new specialized areas in the
medical field. Experts in our society rely on the environment and adapt to the changes of its properties;
they are “codefined by context” (p.182, Stein, 1997). What we call “expertise” is now being redefined not
as a sole property of an expert, but as a combined whole with the environment and artifacts that expert is
dependent upon.

From the theory of expertise, we can summarize the assumptions that we make about human
performances:

1. Expertise can be classified as general, generic, and specific;
2. Structure of expertise can be examined with its components, i.e., knowledge, functions,
   representations;
3. As individuals develop expertise, their knowledge structure and problem-solving strategies
   improve, and they gain automaticity on some of their processes;
4. Expertise is defined with the external aids that individuals use for their tasks, becoming part
   of their expertise.
Distributed Cognition and Expertise Coming Together as One Lens

Netchine-Grynberg (1995), seeking the origin of cognitive tools, recognized three main characteristics of cognitive tools: 1) they are culturally formed and transformed for the functions of real-world human activities, 2) they enclose semiotic structures and provide the means to construct representations that guide actions and ultimately form and activate human cognitive structures during real world activities, and 3) they are goal-oriented and instrumental, forming cognitive relationships and mediating actions between humans and the environment. Individuals, in this perspective, never directly confront reality, but they experience and internalize it through activities using cognitive tools (Netchine-Grynberg, 1995). Although the term “cognitive tool” is an important construct for researchers as well as practitioners, the idea not only has not been well-advanced but also somehow has lost its origin in the course of adopting it for computers in education. The term is sometimes used as a catchphrase and “sold” to teachers as a better way of using technology in the classroom without clearly communicating its implications for instructional methods and the teacher’s role.

The premise of putting distributed cognition and expertise theories together is that the assumptions of the two theories would specify the meaning of cognitive tools, which has remained too vague for researchers and practitioners to make it any useful for their practices. We will return to the above origin of cognitive tools, reinterpret it through the lens of the two theories, and uncover what it means to our research and practice for cognitive tools in education.

The Meaning of Cognitive Tools

Recent studies on expertise include the distributed cognition perspective, stressing on the importance of the role of environment in the cognitive activities of experts (e.g., Lebeau, 1998; Patel, Kaufman, & Magder, 1996). Research and development of expertise and distributed cognition in terms of technology comes together to an important point at this juncture: they both emphasize the significant role of technology in extending human abilities instead of replacing them. Researchers supporting distributed cognition, however, see technology from a very different angle from researchers of expertise, and even look at different kinds of technology. In the theory of distributed cognition, technology is envisioned in a
more general level, existing as one of the various resources in the distribution of cognition. Overlaying
the theory of expertise upon distributed cognition, individuals, environment and tools are viewed as a
system of performance, bringing their qualities and expertise to the situation and interacting with each
other (Patel, Kaufman, & Magder, 1996; Salomon, 1993a).

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 the basic assumptions that
cognition is physically distributed to technology and that expertise is co-defined with experts’ tools, a
cognitive tool can be regarded as having some kind of expertise that allows cognition to be distributed to
it, forming a joint system of learning (see Table 1.1). We can redefine cognitive tools for learning with
this added expertise perspective:

*Cognitive tools are technologies that learners interact and think with in knowledge
construction, designed to bring their expertise to the performance as part of the joint
learning system.*

Learning with technology, when considered with these two theories together, is no longer performed
solely by the learner but as a joint learning system, comprising at least learner(s), tool(s), and activity.

- Insert Table 1.1 about here -

*Cognitive Tools and Expertise of Joint Learning System*

Several conceptual constructs about cognitive tools accompany this new definition based on the
assumptions of the two theories (Table 1.1), reflecting the original characteristics of cognitive tools
described by Netchine-Grynberg (1995). First, cognitive tools can be classified with the human expertise
classification because the attributes of distributed cognition is first determined by its design and the tool
should be classified according to its purpose. In other words, if we regard the kinds of expertise as
representing the layers of capabilities for human performances, the tools that extend those capabilities
should be classified in the same way.

In the same line of thought, cognitive tools form a joint learning system when the distribution is
in action with the learner(s). The way the distribution is structured within the system as well as the way
the expertise of this joint learning system develops should be examined in the same way we have examined human expertise (second and third constructs in Table 1.1). There are two kinds of designs that have major influence on the structure of distribution: the design of tools and the design of activities. The distribution of cognition is structured by implicit characteristics of the cognitive tool (e.g., determined by the software designer) as well as by the explicit aspects of current activities (e.g., determined by the classroom teacher) (Pea, 1993).

These constructs reflect the original cognitive tool idea of capturing realities, having semiotic structure, and mediating human activities for specific purposes. We also need to consider the specific purposes of the tools and what learning activities they are mediating because, unlike real settings, activities are designed in educational context. In the next two sections, we discuss these constructs (kinds of cognitive tools and their activities, and development of joint learning system expertise) in detail.

Expertise in the Tool and the Activity

The term “cognitive tools” is used for explaining many different abstract as well as concrete entities (e.g., both human language and physical calculators are considered cognitive tools). Cognitive tools for learning have been classified based on their different characteristics and purposes. After analyzing the different purposes of tools, Jonassen and Carr (2000) suggested some classes of “mindtools” as semantic organization tools (e.g., databases and concept mapping tools), dynamic modeling tools (e.g., spreadsheets and microworlds), visualization tools (e.g., MathLab and Geometry Tutor), knowledge construction tools (e.g., a multimedia authoring tool), and socially shared cognitive tools (e.g., computer conferencing and computer-supported collaborative argumentation).

Over the two different volumes of *Computers as Cognitive Tools* (Lajoie & Derry, 1993a; Lajoie, 2000), the distinctions among different tools shifted to fit the current pattern of emerging learning paradigms and the corresponding development trend of computer programs. In the first volume, Lajoie and Derry (1993a) categorized the research accounts into modelers (e.g., TAPS; Derry & Hawkes, 1993), nonmodelers (e.g., HyperAuthor; Lehrer, 1993), and the ones merging the two (e.g., DARN; Schauble, Raghavan, & Glaser, 1993). Modeling here meant that the computer program models students’ thinking
processes and diagnoses their performances. In the second volume, Lajoie (2000b) divided the chapters with the tools supporting knowledge-building activities (e.g., SCI-WISE; White, Shimoda, & Frederiksen, 2000) and the tools supporting new forms of knowledge representations (e.g., DNA; Shute, Torreano, & Willis, 2000).

Other researchers have imposed their own theoretical framework for categorizing cognitive tools. Salomon (1993b) suggested that there are two kinds of cognitive tools based on the theory of distributed cognition. The first kind represent performance-oriented tools that learners use to jointly make products with the tools (e.g., Freehand, a graphic program), and the other kind are pedagogic tools that support learners’ cognitive growth (e.g., Writing Partner; Salomon, 1993c). Whether empirically or theoretically-oriented, the existing classifications do not seem to well-characterize computers specifically as cognitive tools per se in ways that imply their usage in real contexts (or of similar tools in the world). Salomon’s (1993b) suggestion that cognitive tools should be evaluated for their potential affordances of cognitive activities and promotion of learner abilities was reflected to some degree in the detailed discussions presented by the aforementioned scholars, but not often in their classifications. There is an obvious need for a classification system that may offer those implications and provide a better basis for examining the interactions between the tool and the learner.

The remainder of this section presents a different way of and a rationale for classifying cognitive tools for learning. Classifying cognitive tools with their potential expertise and distributed structures in carrying out activities may provide some insights on their detailed characteristics as cognitive partners. Tools are discussed in terms of their interactivity with learners and specificity in their purposes. The prominent computer tools in education are reexamined, and the ways cognitive tools relate to learners are reconsidered through the specific lens that theories of expertise and distributed cognition provide.

**Tool Interactivity**

Tools vary in the interactivity they afford with users, ranging from one-way, whereby technology is used as a mere delivery medium of information, e.g., multimedia presentations, to reciprocal interactions, wherein technology actually participates in the cognitive activity of individuals, e.g., a DNA
modeling program. Somewhere in the middle ground is the cognition distributed for a division of labor to offload some tasks or to prevent human-errors with technology, e.g., a calculator or a spell-checker (Perkins, 1993; Salomon, 1993a). Interactivity usually depends on the technology itself, but it is also affected by how the technology is used by individuals and what kinds of activities it is used for.

As physical tools make us physically stronger (e.g., hammer) or faster (e.g., bicycle), computer tools make us smarter, augmenting our cognitive capacities (e.g., speed of processing) (Lave, 1988; Norman, 1993; Pea, 1993). In the ideal level of interaction, technology changes the nature (i.e., process and product) of cognitive activities, allowing individuals to think with the technology in a way that was impossible without it (Pea, 1993). Theories of expertise and distributed cognition converge at this higher level of interactivity, where technology plays an essential role for cognitive activities. Tool expertise mainly characterizes the tool itself, but at the same time implies potential user activities. Ideally, cognitive tools, being considered as “partners,” should be characterized by their reciprocity, remaining at the right end of the interactivity continuum.

A cognitive tool, in our definition, is a cognitive partner that interacts with learners to construct knowledge, bringing its expertise to activities. As a tool, it should be flexible enough to be used for various activities and open to the mindful and creative growth as a joint system with learners. Scholars of distributed cognition, however, suggest that there are certain properties that cannot and should not be distributed to technology, e.g., higher-order thinking (Perkins, 1993). The machine can process a set of rules to perform certain tasks, such as making a representation, tracing the learner’s use of the program, retrieving certain stored knowledge and representations, but cannot understand the meaning of those representations and activities (Salomon, 1993a). The roles of the tools should only be to help humans in meeting cognitive challenges. As argued by many researchers (e.g., Perkins, 1993; Salomon, 1993c), cognitive tools should not take over, but require higher-order thinking from learners for task completion, thus fostering creativity in learners.

Another important property that ultimately humans should perform is executive functions for activities (Perkins, 1993). In the course of constructing knowledge through inquiry and problem-solving,
individuals should decide what to do and where to go instead of the machines making decisions. Taken
the view from expertise theory about relationship between person and technology, technology can only
have roles that can empower and augment higher-order cognitive functions. Technology for experts was
developed as an instrument only to support their inquiry, redefining what it means to be an expert (Stein,
1997). Cognitive tools for learning, therefore, should assume lower executive functions, such as executing
rules, and let learners make the most important decisions during activities.

Tool Specificity

The way cognitive tools are classified here highlights the way expertise is classified in the
literature. As introduced earlier, Patel and Groen (1991) categorized human expertise in three levels
considering its specificity: domain-independent (general) expertise, generic expertise, and specific
expertise. These kinds of expertise can be used to understand what kind of roles tools play in their
partnerships: general cognitive tools that have qualities independent of specific domains to support
various activities; domain generic cognitive tools that bring in basic characteristics to support various
activities in a rather broad area of a domain; and domain specific cognitive tools that deal with more
specific concepts in domains with representations and knowledge specific to narrower topics. The more
specific a cognitive tool is, the more in-depth activities it affords covering less variety of content; the
more general it is, the more variety of activities and contents it affords. There is no superiority among
tools with different levels of specificity because each serves different purposes. A graphics package such
as Photoshop is invaluable for the learner wishing to create artistic visual models of cell structure, but of
little utility to the learner who desires to compute complex equations of planetary motion.

The three primary elements of expertise structure, i.e., knowledge, function, and representation,
then should be used to examine the characteristics of cognitive tools. Embedded knowledge in the tools
can range from widely accepted facts to abstract rules (Anzai, 1991; Patel & Groen, 1991). Functions can
vary from simple information search and rule execution to complex decision-support (Ericsson &
Charness, 1994; Perkins, 1993). Representations can be more concrete (isomorphic) or more abstract
(symbolic). Depending on the specific activities carried out within a domain of study, certain levels of
representations are more beneficial than others. Geographers require precise visual representations of spatial relationships whereas anthropologists may be satisfied with rich narrative representations. Technology can afford various ranges of representations that can be manipulated by learners (Salomon, 1990).

A computer chess game, for example, has specific expertise in chess with knowledge about chess rules and the patterns of chess moves, functions of recognizing patterns and making moves, and visual representations of chess board and moves. The Writing Partner (Zellermayer, Salomon, Globerson, & Givon, 1991) was designed to become a cognitive partner of children learning to write, as in physical distribution of cognition. This program supports meta-cognition about the writing process, so that the young writers can think with the Writing Partner during the process. Seen from the kinds of expertise, the Writing Partner seems to have generic expertise in writing strategies (because it is not a specific kind of writing, such as writing a scientific article) with knowledge about detailed strategies of writing and the function of posing questions to the writer. A computer-supported intentional learning environment (CSILE) (Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989) provides a space for collaborative knowledge construction within an online environment. CSILE supports physical distribution of cognition as well as asynchronous social distribution of cognition, dramatically changing the nature of knowledge construction activity. CSILE can be used across many domains of knowledge so that it seems to have domain-independent expertise—learners bring most of the specific knowledge to work with—with functions of storing and organizing data and representations of concept relations.

Kinds and Characteristics of Cognitive Tools

We first classified the tools into three different categories according to the three levels of expertise that are embodied in the tools (General, Generic, and Specific). Regarding the expertise embodied in tools, we considered their weighted elements that constitute the structure of expertise as to whether the embodied knowledge is more rule-based (deductive) or case-based (inductive) and whether the embodied representation is more symbolic or isomorphic. We then put them into different columns depending on where they are in their functional properties. The functional properties of computer
programs, especially their executive functions, determine their interaction relationship with learners. We scaled the degree of executive functions that computer programs provide with six different levels: lowest, lower, low, high, higher, and highest. The lowest is for those communicating with users only with the same symbol system; the lower for executing learner-created rules with learner created objects; the low for having more embedded rules than the lower; the high for guiding the decisions of learners; the higher for making decisions for learners (or already made in the design); and the highest for having not much learner input and control or no adaptation for individual learners through computer diagnosing.

In Table 1.2, examples of cognitive tools as well as other kinds of computer programs with various degrees of executive functions are presented to demonstrate their relative positions. The heavy lines are drawn around areas indicating those we perceive as cognitive tools. We maintain that cognitive tools can vary in their expertise level, but higher-order thinking and executive function should be left more for the learner, staying at the low and lower level. The dot lines are drawn at the boundaries in order to indicate that the tools may have characteristics of different levels. As the expertise of a person does not have clear boundaries among different levels and can have different levels of expertise at the same time, the position of a particular tool could be argued as variable depending on how other researchers characterize certain tools or how instructional designers and teachers decide to employ them in practice.

Domain-independent (or general) Cognitive Tools

Some cognitive tools basically have general qualities independently of domains. The descriptors of each row in Table 1.2 (i.e., knowledge and representations) are not about the learner’s gaining knowledge or resulting artifacts, but about what the tool holds in order to interact with the learner. Domain-independent cognitive tools typically use certain symbol systems and symbolic representations to communicate with learners during the process of building knowledge and making products. When the degree to which a tool performs executive function is relatively low, there are more possibilities for various forms of activities and products. Examples are authoring tools as one with low executive functions, and productivity tools as one with more embedded rules for output products.
Authoring tools are alternatives for programming languages whose interfaces are scaffolded by symbolic metaphors, such as index cards, stages, frames, and trees. Productivity tools, such as databases, spreadsheets, and concept-mapping tools, are programs originally developed to increase workplace productivity by organizing knowledge and information in a more accessible manner. Researchers saw the values of using these two kinds of general tools for educational purposes and suggested using them as cognitive tools for learning whereby learners become designers by constructing “knowledge representation” products with the tools (Jonassen & Reeves, 1996). Erickson and Lehrer (2000) studied students in seventh grade using an authoring tool called HyperCard (using the metaphor of index cards) throughout a school year and described their processes of understanding the role of links in their hypermedia products and how their understandings were reflected in their design of HyperCard stacks. Authoring tools can be used flexibly by users for creating various kinds of knowledge representations such as a multimedia presentation or a website.

Productivity tools, on the other hand, can usually afford only certain kinds of representations (e.g., concept-mapping tools afford the creation of maps and outlines). Productivity tools are highly accessible to many classroom teachers and can be used for knowledge organization tools in many different disciplines. Concept-mapping tools have been extensively studied by many researchers and found to be very helpful not only for individual thinking activities, but also for group decision-making processes or knowledge-building activities in face-to-face classes or over the Internet (e.g., Hewitt & Scardamalia, 1998; Jonassen, 1993).

Domain Generic Cognitive Tools

Some cognitive tools possess basic characteristics to support various activities across a broad area of a domain. These tools are more prevalent in science and mathematics where representation of complex knowledge is very important in the problem-solving processes. Generic kinds of cognitive tools have the rules that underlie a domain, such as physics and chemistry, and usually produce symbolic representations, such as graphs and other visualizations of data. With some executive function embodied, generic cognitive tools have more structure for what is expected from the learners and for the representations.
With even lower executive functions, learners often this structure out of the variety range of possibilities. The example for the latter is microworlds, and for the former are visual representation tools.

StarLogo is a well-known microworld that helps learners to explore systems dynamics. StarLogo operates according to the rules created by learners to produce a dot or collection of dots on the screen interacting in the represented world (Resnick, 1996). Learners create representations of real-world systems by deciding on which system elements work in what ways within StarLogo. Other generic cognitive tools start with certain sets of visual representations to enable students to approach problems (e.g., Kozma, 2000a). To learn about dynamic systems, Stella requires learners to specify factors that stimulate the system changes so that it generates certain visual representations, such as diagrams and graphs (Resnick, 1994).

Other tools, such as Model-It and MathWorlds, combine these two levels of functionalities. Using Model-It, learners can create various levels of complexity within dynamic systems, such as stream ecosystems and human body systems, by importing graphics to contextualize their models and defining the factors and the relationships among components of a system (Metcalf, Krajcik, & Soloway, 2000). Learners test and evaluate the model using its graphing tools. MathWorlds provides an environment in which learners define how interacting animated characters’ motions are connected using graphs that can be manipulated (Roschelle, Kaput, & Stroup, 2000).

*Domain Specific Cognitive Tools*

Cognitive tools that deal with concepts in specific domains use more concrete representations and encompass more knowledge about individual cases in addition to any rules that govern them. These tools are similar to the domain generic cognitive tools, but they deal with more specific content areas. Some of these tools with lower executive functions allow learners to create their own cases with which they can work, whereas others with more structure provide choices and/or database of cases. An example of the former is the manipulative tool, GenScope, and of the latter is the simulation tool, MicroObservatory.

GenScope, specifically designed for the domain of genetics, allows students to manipulate objects and observe their behaviors (Horwitz & Christie, 2000). GenScope provides six different observational
levels (i.e., molecules, chromosomes, cells, organisms, pedigrees, and populations) for genetic
descriptions with their representation and manipulation means, which can be flexibly devised or
restrained for use depending on the particular levels of learners and activities (Horwitz, 1999; Horwitz &
Christie, 2000). GenScope is an example of a specific expertise cognitive tool, as each case is run by its
implicit rules. In this example, tools do not give learners any kind of correct visualizations or models so
that learners themselves have to decide what and how to model or visualize phenomena with what values.
The cognitive function of these tools is to bridge the space between the decisions of learners and the
visual products.

Simulation tools are similar to manipulative tools in observing object behaviors, but they do not
allow learners to manipulate objects. MicroObservatory, for example, is specifically designed for
astronomical observations of the sky, which provides a network of five automated telescopes controlled
over the Internet from which learners can take images for their own scientific observations (Sadler, Gould,
Brecher, & Hoffman, 2000). MicroObservatory was set up for an educational use to simulate a real-world
scientific tool.

Tools that Traverse Boundaries

The tools described above cannot be said to belong to their boxes at all times as illustrated in
Table 1.2. Some tools encompass multiple levels of executive control and others include some functions
outside of the defined boundaries. Some tools are even designed to allow multiple representations with
various levels of specificity in order to provide diverse channels of understanding (Kozma, 2000b). A few
award-winning multimedia programs that are primarily structured for exploratory lessons also employ
cognitive tools as part of their activities within a lesson. Exploring the Nardoo, a structured multimedia
environment wherein learners work within the specific content area of ecology, uses metaphors of real
world problems and realistic settings that involve cognitive tools (e.g., a note-taking facility, genre
templates, and interactive simulators) for problem solving activities (Harper, Hedberg, Corderoy, &
Wright, 2000). Bio-World, SICUN, and RadTutor provide simulated environments for medical
informatics, giving students opportunities to practice their problem-solving and hypothesis-testing skills.
using provided cognitive tools (i.e., evidence palette, online library, and online simulations) within the context of managing clinical cases (Lajoie & Azevedo, 2000).

As the lowest level of providing specific functions to perform tasks, programming languages require a heavy cognitive load for most learners to understand them before they can focus sufficiently on other authentic activities. Logo was invented to provide an easier programming language for children. Logo evolved into StarLogo, and it is now scaffolded with a more visual interface (Jonassen & Reeves, 1996; Resnick, 1996). With the scaffolded visual interface, StarLogo shares some similar characteristics with authoring tools.

In some cases, programming languages are not only the means, but the ends for learning. Recognizing the problem of novice engineers’ over reliance on the finished product to learn the process, INCENSE was created as a scaffolded learning interface that helps novice students to learn the process of software engineering (Akhras & Self, 2000). Some researchers have employed expert system shells with IF-THEN rules in classrooms, requiring learners to actually build production rule expert systems recognizing that people who design expert systems gain considerable knowledge about expert performance (Jonassen & Carr, 2000). With its scaffolded learning interface in the area of programming, INCENSE has aspects of manipulative tools we categorized as domain specific cognitive tools.

Programs that provide general expertise with high executive functions mostly expect users to perform better by using them, but ultimately to gain “cognitive residue” of certain cognitive skills, such as inquiry skills and meta-cognitive skills. Writing Partner (Salomon, 1993) guides students’ writing process, but the purpose is not for learners to use this program for every writing task, but to master the way they think about writing by working with this program. STAR.Legacy (Schwartz et al., 2000) and SCI-WISE (White et al., 2000) are also structured environments that teachers may use for different content to help students master the process of inquiry as their meta-level expertise. These kinds of computer programs have been introduced as cognitive tools. However, the main purpose of these programs appears to be the learning of meta-level skills, and the purpose of using them for cognitive activities is a secondary concern.
Programs providing more specific levels of expertise with higher executive functions can include intelligent agents and expert systems. One such program is a children’s programming environment called KidSim that enables learners to program behaviors of objects not by writing code as in programming languages, but by moving objects on the screen. The intelligent agent underlying KidSim remembers and recreates the movements (Smith, Cypher, & Spohrer, 1997). In many cases, these programs provide some flexibility for learners to be creative, but variations in activities are relatively limited. Some researchers identify these types of programs as cognitive tools because they unburden the cognitive load of learners. However, we put them outside of the boundary of cognitive tools because the primary judgments and decisions are not usually made by the learners.

The more control the computer has over learners’ behavior, the less cognitive flexibility it affords. The general production wizards found in productivity tools or authoring tools guide users through the process of producing something in a standard way by simply filling in templates or responding to a series of questions. This provides an easy way to produce something quickly, but this is not the way that learning should occur. Intelligent tutoring systems often make good decisions for learners by diagnosing their levels and tutoring accordingly (Salomon, 1990), but they also cannot be considered as cognitive tools that learners employ for their learning activities. Information presentations and computer-based tests (non-adaptive) may exemplify computer programs with the highest executive functions because what is on the screen will be the same for every user, giving little or no control over the process to the learners.

**Expertise Manifested in the Design of Activities**

A tool’s purpose changes depending on its use, i.e., the user’s activities with the tool. The difference between the expertise of persons and that of tools is that the former can be developed (or degraded) over time whereas the latter is designed and remains the same as long as the tool designer does not make modifications. Changes in the performance of a cognitive tool happen when the partnering person changes its use, e.g., when a graphing calculator is used to display the distribution of test scores, and then used to analyze a pattern of physics experiment results.
The design of cognitive tools and activities for learners should be distinguished from that of other kinds of computers and activities. Cognitive tools are for profound thinking, similar to those of people engaged in real problem-solving situations. We have to think about these different purposes and meanings of tools in designing and using them for learning activities. Activities using cognitive tools should convey the common usage of similar tools in the world as well as the expertise of the people using those tools. The design of a tool becomes worthwhile only because of the meaningful activities it can afford (Salomon, 1993c).

Going back to the Oppenheimer’s (1997) analogy of hammer and carpentry, we should not teach hammer instead of carpentry, but we cannot do carpentry without a hammer. The ways that cognitive activities are performed in the world also cannot be described without describing the roles of tools (Perkins, 1993). Many domains of experts now use computers as a part of their professional activities, varying from organizing and representing their thinking to creating actual products (Ericsson & Smith, 1991). Indeed, for scientists, the advancement of knowledge in many scientific domains is now so dependent on computers that computer modeling has become as important as theory construction and experimentation (Pagels, 1988). As the use of computer tools changed the processes and outcomes of activities in the world, tools and activities in the classroom should change to reflect the nature of real world practices.

How learning activities are carried out in classrooms for certain topics can be very different depending upon the different levels of cognitive tools adopted. To use a cognitive tool, the teacher and/or learners usually must change or modify their learning activities. With the same topic in a subject, you could use a general cognitive tool, a generic cognitive tool, or a specific cognitive tool. To learn about genetics, learners could engage in manipulation and observation of species using Genscope. On the other hand, the teacher could design a task with microworlds that focuses on understanding underlying DNA rules to create a dynamic system. Using a multimedia authoring tool, a general level cognitive tool, may involve a completely different kind of activity, such as making a multimedia presentation about genetic mutation. The biggest difference among these activities would be their similarities to the practices of real-
world experts. The more specific the tools are, the more similar the activities would be to that of experts, manifesting expertise in the world.

Some researchers have developed curriculum that incorporates the experience of real-world experts using tools. The Learning Through Collaborative Visualization (CoVis) project promotes open-ended inquiry within constructivist learning environment (Edelson, Pea, & Gomez., 1996). CoVis is based upon a technology-supported inquiry learning (TSIL) design framework that includes the identification of motivational context, the selection and sequencing of activities, the design of investigation tools, and the creation of process support such as scientific visualization software (Weather Visualizer and World Watcher) and other technological supports for learning (Collaboratory Notebook, Internetworking Tools) (Edelson et al., 1999). One CoVis study investigated the implementation of the Global Warming Curriculum within a 6-week period, during which middle and high school students prepared briefings for a fictitious global warming conference. The study showed that CoVis project provided learners with a coherent motivating context assuming the role of scientists, but the study also raised the issue of the large time commitment needed to implement such in-depth inquiry-based learning (Edelson et al., 1999).

The Development of Joint Learning Systems

Engelbart classified four basic “human augmentation means (cited in Rheingold, 1985, p. 182)”: artifacts (physically designed to manipulate other things), language (as means to think and attach meanings to the world), methodology (as in method, procedures, and strategies for problem-solving activities), and training (for skills in using other means). He visualized an augmented system as a trained human being together with a set of artifacts, language, and methodology. These four classes manifest both ideas of distributed cognition and expertise in that the human is dependent on the environment (artifacts and language) (i.e., physical and symbolic distribution) and is trained to use skills (methodology and training) (i.e., development of expertise).
When the computer was first introduced into education, it was viewed as a mere delivery medium of established cognition, not much different from a book or an organized shelf of books (Pea, 1993). Outside of schools, the role of computer tools has become increasingly important in highly intellectual tasks as critical means for completing tasks (Pea, 1993; Salomon, 1993b; Salomon, Perkins, & Globerson, 1991). As the participation of a person with different set of skill in a task changes the nature of an activity, computers have changed the nature of tasks in many domains (e.g., statistical analysis). Computers as cognitive tools beyond delivery media lead to fundamental changes in cognitive activities, ideally to producing higher levels of thinking (Cobb et al, 1997; Vygotsky, 1978).

The knowledge and performance that result from cognitive effort, therefore, cannot be attributed solely to a person because they are the product of joint participation among people and tools (Karasavvidis, 2002; Salomon, 1993a). The outcomes of distributed cognition include not just constructed knowledge or performance, but also resulting cognitive process and distributed structure through the joint relationship. These implicit outcomes of joint thinking become important parts of a person’s cognitive development. Development of cognitive processes mediated by the affordances of the joint system produces even a stronger structure of distributed cognition (Salomon, 1993a).

In the research of chess expertise by (Charness, 1991), human chess expertise was studied with a computer chess game opponent. The expertise of any given chess player, ranked as grandmaster, international master, master, expert, and so forth, appears as a stable quality of the player. The player’s use of this expertise, however, depends largely on what kind of move the computer makes (which depends on the previous move of the player) and what kinds of patterns the player has encountered before; the player even discovers new patterns and strategies as he or she proceeds. The player’s cognition is distributed to the computer socially (as an opponent player), symbolically (by sharing same conventions), and physically (as an object).

In learning situations, learner(s) and tools with a meaningful task form a joint system of learning. Figure 1.1 illustrates our suppositions on how a joint learning system performs within and outside the
designed activity (task) and how its performance outside of the boundary changes over time, as its
erpertise develops as a system. The participants of the joint learning system (the learner(s) and the tool)
come to share and develop shared language and methodology.

- Insert Figure 1.1 about here -

Growing Expertise of the Joint Learning System

Salomon et al. (1991) regarded computers as “partners in cognition” when learners work with them during cognitive tasks. What does it mean to become a partner? Human partners bring their unique expertise to a team; partners strive to know about each other’s strengths and weaknesses to build their relationship and work effectively together. Cognitive partnerships with computers take place in a similar fashion and require substantial efforts to become a strong team. When partners of distributed cognition are continually involved in activities together, the distributed system is likely to develop into a more sophisticated relationship. The sum of isolated cognitions cannot adequately represent the workings of the distributed cognition; thus the cognitive growth of an individual cannot be understood without understanding the development of joint cognitive relationships. Theories of expertise and distributed cognition shed new light on the partnerships between humans and their cognitive tools.

Once partners join a team with their expertise, they strive get to know each other to perform their tasks. Similarly, when new technology is introduced to an individual in a problem-solving situation, the person has to deal with this new relationship with technology. Learners do not automatically think productively with cognitive tools from the start. The cognitive load of a tool’s interface is highly evident, making the affordances of the tool less obvious to the learner, and thus, the partnership of the joint system remains weak for some time (Pea, 1993). With a new cognitive tool, higher-level thinking may be limited as long as users struggle to make the technology itself work. Then the cognitive load devoted to the tool use per se reduces as individuals grow accustomed to its use, and they are able to engage in higher order thinking. In Figure 1.1, the performance of joint learning system outside of the designed activity is first focused more on problem areas, such as improper tool use, misunderstanding and troubleshooting.
When individuals see the value of using tools in their cognitive activities, they are willing to engage in the process of learning the tools so that they can adapt them for their activities (Perkins & Grotzer, 1997; Wertsch, 1998). Expertise of the learner and the joint system grow with each other in a synergistic way. The learners’ growing expertise in the domain and increasing familiarity with the tool (i.e., knowledge structure, problem-solving strategies, and automaticity) are important if the learner is able to take advantage of the expertise of the tool. Likewise, the performed expertise of the tool stimulates the development of the learner’s cognition, resulting in stronger joint expertise. Learning to use a tool, therefore, is not a process that happens only at the beginning but is rather an ongoing process; learners discover more affordances of tools and even refine their own abilities as they master the tools and develop more effective distributed relationships. In other words, the interface of the cognitive tool becomes less visible to the learners, the affordances of it more obvious, and the partnership of the two stronger. In this way, the new tool, the existing environments, and the person together contribute to the distributed cognition in activities (Pea, 1993). Eventually, the joint system synergy enable the learner to understand the world with more profound meanings (Falbel, 1991; Salomon & Almog, 1998).

The development of distributed cognition might go through a major transitioning phase when confronting novel situations. When a unique problem-solving situation is thrown into a distributed cognition structure, individuals again have to find novel uses of tools and adjust the structure and workings of distributed cognition. At the same time, the growth in the joint system changes the way activities are carried out. The structure of joint expertise transforms as elements (i.e., knowledge, function, and representation) are modified or take new forms, altering the way they interact with each other. The strengths and weaknesses of both the learner and the tool become clearer by finding the roles of each in relation to the activities (Pea, 1993). The focus of their activities outside of the boundary (Figure 1.1) then becomes on the explored areas, such as discovered tool use, creative learner roles, and explored resources. Cognitive tools should be designed to be flexible and open to this growth, providing learners with opportunities to be mindful and creative in their activities (Jonassen & Reeves, 1996; Salomon et al., 1991).
Research on the Joint Learning System

In the perspective of distributed cognition, environments and their sub-components are seen as integral parts of human cognitive activities. From this view, individual ability and distributed structure should be considered together to understand cognitive activities (Nickerson, 1993; Salomon, 1993a). It has been recognized that a distributed system of cognition cannot be understood by examining its parts in isolation, and thus recent research in cognition moves away from just seeing an individual as a unit of analysis to viewing a system of individuals and the environment in action as a legitimate unit of analysis (e.g., (Brown et al., 1993; Hutchins, 1995; Lave, 1988; Pea, 1993; Perkins, 1993; Wertsch, 1998).

The Extended Unit of Analysis

For the research on cognitive tools, the unit of analysis should be learners together with computers, in order to encompass their intellectual partnerships as they are forming and evolving. The extended unit of analysis includes a cognitive tool as an inseparable entity for learner capabilities; at the same time, each tool should be considered as having its own contributing qualities (Salomon, 1993a). We believe that the distributed cognition plus expertise view suggests a way to look at two kinds of completely different subjects (i.e., learners and tools) as partners and interacting constituents of a compound system. Detailed concepts of these theories (e.g., elements of expertise structure: knowledge, function and representation) becomes important constructs for understanding the qualities of each. The performance of the tool, therefore, should be given a similar amount of attention to that of learners, if not the same.

Researching the Action

Understanding the complex nature of a distributed cognitive system requires studying it in action during the time when the interaction is actually happening—not before or after (Pea, 1993; Wertsch, 1991). The learner or the tool alone without any interaction is no longer a distributed system even though there is a potential relationship between the two. Just as any kinds of designed artifacts have intended uses for certain types of activities, educational settings usually have activities that are designed for potential relationships among interacting units to promote opportunities to learn. The emergent characteristics of a
Distributed cognition can be seen from both analytic and systemic views. From an analytic view, the distribution is a set of cognitive functions coming together to perform a task; from a systemic view, the distribution is a natural status of a cognitive task performance (Nickerson, 1993). The structure of cognitive distribution can be designed and studied to facilitate cognitive activities (analytically) as well as be observed and studied as a phenomenon (systemically) (Bell & Winn, 2000; Pea, 1993). Whether by design or by nature, the structure of distributed cognition is not a static condition, but dynamically embedded in human activities; the structure evolves and changes over time, thus holding both intentional and natural characteristics (Pea, 1993; Perkins, 1993).

Implications for Research and Practice of Cognitive Tools

The term, “cognitive tool” is used with different conceptual meanings in other fields of knowledge, such as the studies of language as a cognitive tool. In the field of Instructional Technology, cognitive tools have been viewed too simplistically as tangible objects that learners use for their learning. Rethinking cognitive tools, therefore, is important if we are to advance the meaning of the term for design, development, research and practice beyond its abstract conception (Table 1.3). In this paper, we have recommended the theories of distributed cognition and expertise to advance ideas and research about cognitive tools. These two theories together help us examine the expertise of every participant of an activity, including a cognitive tool, which contributes to the distributed cognition in performing the task. Several principles for the research and development of cognitive tools can be recapitulated from the discussions above.

- Insert Table 1.3 about here -

**Implication 1. Tool Design: Differentiate the Capabilities of the Tool from Those of the Human**

Some argue that we need to be aware of the potential losses in our intellectual abilities when using any new intellectual tool (Egan, 1998). In terms of cognitive tools for learning, we should think about these effects even earlier, when we design them. As the cognitive tool participates in the cognitive
activity of learners, it alters the way they think and act. Understanding how the tool may enable and
constrain the possible activities within the learning environment should help us design tools that actually
empower learners in their thinking (Kozma, 2000b). The design of tools should be centered on the things
that computers can do better than humans without taking over the most important cognitive tasks of
learners (Dreyfus & Dreyfus, 1986; Norman, 1993).

Initially, computer tools were developed and researched specifically to capture the expertise of
experts within the field of artificial intelligence or to be used in the classrooms for teaching school
subjects. The major mistake of both traditions was their focus on the design of machines that resemble
what we already have in our environment (i.e., experts and teachers). The design of cognitive tools for
learning should be founded on the complete understanding of appropriate learning theories and the unique
processing capabilities of computers (Kozma, 2000b). To this end, the first thing we need to remember (in
relation to the theory of distributed cognition) is that tools designed to extend cognitive capabilities of
learners should reflect what it means to have a distribution of cognition. Many computer tools are
competitively developed nowadays for similar uses, pitching any special features that differentiate them
from their competitors. A tool’s distinctive qualities from other tools, however, are not as important as its
affordances that are distinctive from humans for contributing to the performance of tasks.

Implication 2. Activity Design: Regard Cognitive Tools as Part of Human Expertise and Situate Them in
Appropriate Activities

Today’s real-world cognitive tools are part of the capabilities of experts. Hence, we should think
about the design of cognitive tools for learning in relation to the theory of expertise. Tools in general are
integral parts of human activities, and the capacity to use tools is critical in judging our competence levels
in many domains (Cobb et al, 1997; Wertsch, 1998). Computerized tools nowadays are increasingly
critical parts of our cognitive activities, and in many field, expertise can not be accounted for without
understanding experts’ use of their tools. The design of cognitive tools should allow learners not only to
use the tools to learn specific content for planned lessons, but also to use them in other relevant problem
solving situations in ways similar to how experts use their tools for various problems. We should not
attempt to assess the knowledge of learners without their cognitive tools any more than we would assess the expertise of scientists without their tools.

Computers as cognitive tools are essential for learners to be active in contemporary constructivist learning environments. Ideally, the application of cognitive tools for learning in schools or other educational contexts (e.g., online) should resemble the use of cognitive tools in the world. This means that activities in the world, including their processes and products, are replicated in the classroom or in the online learning environment. Cognitive tools thus should be adopted to transform the way learners interact in the classroom from the passivity of lectures to doing authentic tasks similar to the ones pursued in the world (Herrington, Oliver, & Reeves, 2003). The activities should be planned to afford learners’ opportunities to design their own solutions to problems, taking advantage of the capabilities of technology (Kozma, 2000b).

Implication 3. Research and Practice for the Partnership: Assess Learners with Their Tools

By perceiving a tool as a partner of cognition working together towards an activity such as solving a problem or accomplishing a task, the boundaries between cognitive process and the outcomes of cognitive process become fuzzy. The skills and strategies that learners gain through the partnership (the effect “of”) become learners’ capabilities to perform better during the partnership (effect “with”). Thus, learning can only be assessed appropriately by examining a learner’s performance with a tool. Some disappointment concerning learning performance derived from the adoption of cognitive tools comes from the measurement of the learner’s cognitive outcomes in a completely different situation, i.e., without the tool (Salomon & Almog, 1998).

Research on learning with cognitive tools, therefore, should account for the various aspects of learning situations that we have discussed. The researchers should be able to scrutinize the effects “with” a cognitive tool and the resulting effects “of” it on the learners, which ultimately influence the effects “with” the tool when learners work with it again. These evolving effects and various transitions can only be understood when we observe learners working with the tool over a longer period time so that they actually build their relationship with the tool. The proposed integrated framework for cognitive tools
provide us some potential ways to examine computer tools as to what affordances tools should have in what areas of expertise in what levels with what kind of structures, and what roles we expect learners to play in the structure of distributed cognition. Various alternative research approaches should be adopted in order to capture this complex cognitive relationship within the distributed system. As important bases of our theory, practice, and research, the understanding of this relationship should contribute to pedagogical and instructional design knowledge in education (Kozma, 2000b).

Implication 4. Research and Practice for Growth: Study Learner Initiation and the Development of the Distributed Cognitive Relationship

The mastering of nature and the mastering of behavior are mutually linked, just as man’s alteration of nature alters man’s own nature (Vygotsky, 1978, p.55). “Ms. S., I don’t have a HyperCard mind,” blurted a child during the research conducted by Brown et al. (1993). Despite their high expectations, the researchers found that children were not able to exploit many of the complex features of HyperCard successfully (Brown et al., 1993); the affordances of the tool were provided, but never used. It is important to provide learners many opportunities to initiate distributed relationships with tools and learn how to master and work with tools in cognitive activities that require the expertise of tools. They also need to learn how to design the structure of distribution by exploiting critical expertise of other learners and certain tools among various resources. The development of expertise with cognitive tools is one of the most important aspects of human activities and performances outside of school (Pea, 1993).

To make a successful transition to the new distribution relationship, teachers and instructional designers should allow more time for the skills and knowledge development of individuals with gradually fading degrees of external support (Glaser, 1996; Salomon, 1993a). Learning activities should be focused on mastering various features of the tool itself while maintaining the relevance of the real context of problem solving situations. Teaching the tool without a meaningful context is detrimental to advanced learning. As learners work with the tools they should become confident in assessing the problem situations, developing their own strategies, and monitoring their progress (Kozma, 2000b). Once they make this transition and gain expertise with the tool, they will recognize when to rely on the tool and
when not to (Pea, 1993; Salomon, 1993a). Evolving expertise reveals more capacities and functions of the tool in the performance of tasks, and this continuous reciprocal process that happens during learning activities makes expertise grow even more (Salomon, 1993a).

Final Thoughts on Cognitive Tools

Researchers often make analogies to physical tools to explain cognitive tools. However, the analogy does not last once researchers get into the substantive conversations about cognitive tools. In the earlier research literature, intelligent agents, which we classified as outside the margins of cognitive tools in Table 1.1, were perceived as cognitive tools by becoming advisors or by hiding complex rules behind the computer and letting users do the easy hands-on tasks. We believe these tools have different purposes from cognitive tools. Consider a physical tool, say a tennis racket, specifically for the effects “with” and “of” its use. A tennis racket extends human capabilities (e.g., increasing probabilities of reaching the ball and hitting it to a certain direction) by virtue of its involvement in the game’s activities together with the person (effects “with”). The role of a coach, by contrast, is giving advice, e.g., a coach’s revealing of rules and helpful tips may help the player master the game. The physical residue of using the racket (effects “of”) could be a stronger arm and healthier body, which transfers to other kinds of athletic activities, whereas the cognitive residue of coaching could be more knowledge about how to grip and swing the racket. We do not try to examine how well people play tennis without giving them a racket, expecting them to play as good as they could with it (Salomon et al., 1991).

The role of cognitive tools is similar to that of physical tools, which is truly to provide an extension of our cognitive abilities, but there is an important fundamental difference. The resulting effect of using real cognitive tools should be the better use of the tool itself for cognitive activities as well as substantial cognitive growth that transfers to other kinds of cognitive activities. The essential nature of a cognitive tool cannot help someone learn without the appropriate use of a tool, but the nature of a cognitive tools differ from that of traditional tools in that as expertise grows we can adapt them for new creative activities. No amount of practice and coaching will enable someone to use a tennis racket to play
golf, but practice and guidance with using cognitive tools may yield to innovative ways of thinking and problem solving that educators have not even begun to imagine.

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and organization tool. In S. P. Lajoie (Ed.), *Computers as cognitive tools: No more walls* (Vol. 2,


Table 1.1

Theoretical Assumptions and Proposed Conceptual Constructs of Cognitive Tools

<table>
<thead>
<tr>
<th>Distributed Cognition</th>
<th>Expertise</th>
<th>Cognitive Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Distribution</td>
<td>1. Expertise kinds</td>
<td>1. Tool expertise kinds</td>
</tr>
<tr>
<td>2. Distribution by design</td>
<td>2. Expertise structure</td>
<td>2. Learner-tool expertise structure</td>
</tr>
<tr>
<td>3. Distribution in action</td>
<td>3. Expertise development</td>
<td>3. Learner-tool expertise development</td>
</tr>
</tbody>
</table>
Table 1.2

Examples of Different Kinds of Cognitive Tools and Their Relative Positions

<table>
<thead>
<tr>
<th>Expertise Knowledge Representation</th>
<th>Executive function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lowest</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Higher</td>
</tr>
<tr>
<td></td>
<td>Highest</td>
</tr>
<tr>
<td>General</td>
<td></td>
</tr>
<tr>
<td>K: symbols</td>
<td>Authoring tools</td>
</tr>
<tr>
<td>R: symbolic</td>
<td>Productivity tools</td>
</tr>
<tr>
<td></td>
<td>Meta-level programs</td>
</tr>
<tr>
<td></td>
<td>Production wizards</td>
</tr>
<tr>
<td></td>
<td>Information</td>
</tr>
<tr>
<td></td>
<td>presentations</td>
</tr>
<tr>
<td></td>
<td>Computer-based tests</td>
</tr>
<tr>
<td>Generic</td>
<td>Programming</td>
</tr>
<tr>
<td>K: rules</td>
<td>languages</td>
</tr>
<tr>
<td>R: symbolic</td>
<td>Microworlds</td>
</tr>
<tr>
<td></td>
<td>Visual representation tools</td>
</tr>
<tr>
<td></td>
<td>Intelligent</td>
</tr>
<tr>
<td></td>
<td>agents; Expert</td>
</tr>
<tr>
<td></td>
<td>tutoring systems;</td>
</tr>
<tr>
<td></td>
<td>Multimedia</td>
</tr>
<tr>
<td>Specific</td>
<td>Manipulative tools</td>
</tr>
<tr>
<td>K: rules/cases</td>
<td>Simulation tools</td>
</tr>
<tr>
<td>R: isomorphic</td>
<td></td>
</tr>
</tbody>
</table>
Table 1.3

The Concept, Design, Application, and Research of Cognitive Tools

<table>
<thead>
<tr>
<th>Cognitive tool</th>
<th>Concept</th>
<th>Design</th>
<th>Application</th>
<th>Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>Technologies that learners interact and think with in knowledge construction, designed to bring their expertise to the performance</td>
<td>General tool</td>
<td>Designed to reflect expertise of the world</td>
<td>Analytic approach to the distribution</td>
</tr>
<tr>
<td>Joint learning system</td>
<td>Joint learning system in action: learners-tool-activity</td>
<td>Growing expertise of joint learning system</td>
<td>Systemic approach to the evolution of expertise</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1.1 Joint learning system and its changes in performances
CHAPTER 2

CREATING A UNIVERSE WITH COMPUTER:
CHARTING THE STRUCTURE OF DISTRIBUTION BETWEEN LEARNER AND A COGNITIVE TOOL FOR SCIENTIFIC INQUIRY

2 Kim, B. & Hay, K. E. To be submitted to Cognition and Instruction
Abstract

This paper describes a study focused on the design issues of a cognitive tool by examining and comparing interactions across different groups of learners engaged in common activities. The main purpose of the study was to examine the roles of a cognitive tool and learners, and the functions of a specific pedagogical approach in their tool use, in order to improve the designs of the collective learning system including learner, cognitive tool, and learning activity. The assumption was that the tool (Astronomicon) and the way the tool is used (Modeling-Based Inquiry) may promote appropriate design and use of a cognitive tool for scientific inquiry. The results of study provide important implications for the future design efforts to adopt advanced cognitive tools for learning.
Creating a Universe with Computer: Charting the Structure of Distribution between Learner and a Cognitive Tool for Scientific Inquiry

Tools in general are integral parts of human activities, and the ability to properly utilize tools is a key component for successful performances (Cobb et al., 1997; Wertsch, 1998). In this information age, computerized tools are becoming more critical to our daily lives in various levels of cognitive activities, say, from family budget organization to weather forecasting. Especially in professional science and mathematics, experts use advanced technologies to enable and extend their inquiry processes (Roschelle, Kaput, & Stroup, 2000).

Inquiry-based pedagogy strategy is adopted with the belief that the learning of scientific content should be grounded in scientific investigation processes and its applications to real questions (e.g., National Research Council’s National Science Education Standards). The inclusion of certain technologies in inquiry-based pedagogies, therefore, should come from the understanding of the way that the modern tools of scientists, such as modeling and visualization technologies, support inquiry processes.

These contemporary demands drive the development of technology that supports authentic learning activities (e.g., a program to measure physical properties of objects and graph relationships among properties) rather than decontextualized activities (e.g., a tutorial explaining physics rules). Moving beyond the level of substituting teacher or book for the sake of technology, researchers started research and development of cognitive tools resembling those of scientists for inquiry-based learning. These tools can be developed with elaborate features intended for higher-level learning and thinking, but problems arise when their value is not seen by the learners and/or not reflected in learning activities. While they reported some successes in their implementations, at the same time they reported that learners were often unable to use the various features of tools to go beyond modest expectations (e.g., Brown et al., 1993; Edelson, Gordin, & Pea, 1999; Spitulnik, Krajcik, & Soloway, 1999). It is easy to regard learners incapable of using the complex features, or the tools having unnecessarily complicated functions, which are not always the causes for the lacking uses of advanced functions.
In order to better support the learners’ use of the tools for scientific inquiry, the learning environment, including learning technology and activities, should be carefully designed and studied. More investigation is needed on what features are used and how they are used for certain cognitive tasks, in order to decide what is missing and what needs to be done. The purpose of this study is to examine the roles of a cognitive tool and learners, the effects that learners have by working with it, and the functions of specific pedagogical approach in their tool use, in order to ultimately improve the designs of the collective learning system including learner, cognitive tool, and learning activity.

The design of learning environments and technology should be based on our understanding of what constitutes the learning environment and activities (Land & Hannafin, 2000). The cognitive tool in this study was designed and developed while the curriculum was being developed: In other words, most of the features of the tool are designed to accommodate the curricular needs in an undergraduate introductory astronomy lab. The assumption is that the tool (Astronomicon, a software program designed to model solar systems) and the way the tool is used in the setting (Modeling-Based Inquiry) may promote appropriate design and use of a cognitive tool for scientific inquiry.

This paper first delineates the conceptual and research framework for cognitive tools for scientific inquiry, which we have more broadly suggested elsewhere (Chapter I), describes a case where the designed tool and instructional activity are well-integrated, describes what the distributed cognition looks like in this case, and finally provides implications for future research and practice.

Conceptual Framework

The theoretical foundations of this research come from the theories of distributed cognition and expertise. Distributed cognition is a view that cognition resides not only in a person’s head, but is distributed among people, artifacts and symbols (Salomon, 1993). Cognition is distributed among participants of an activity (i.e., computers and learners for a learning activity) in order to perform tasks together instead of the tasks divided up to finish separately. The computer is no longer perceived as a mere delivery medium, but as a technology with unique capabilities that complement learners’ cognition (Kozma, 1991). Learner, tool, and activity form a joint system, and interactions among them build the
distributed structure of thinking and working together. Distributed cognition theory suggests that
technology assisting the cognitive tasks of learners enhances their reasoning and decision-making;
nonetheless, the ideas of how we should decide what to include as functions of technology, how those
functions could work with learners, and how we should study all these have not been fully established.

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). Technology used in professions partly defines expertise, as experts
rely on the environment and adapt to its changes (Stein, 1997). Within the field of instructional
technology, theories of expertise have been discussed and employed mostly in such areas as intelligent
tutoring systems and expert systems, where the computers are used to model the expert processes.

In contrast to this approach, we should consider the contribution of the computer as part of the
expertise of a distributed cognitive system, instead of only representing an expert’s cognitive processes.
In this way we will be able to go beyond simply acknowledging the distributed nature of a particular
learning system, to exploring how that system develops in cognitive tasks and how we can support and
design for the effective learning system. The study of the knowledge and process for cognitive tasks
needed from the learners as well as from the computers should suggest important implications for the
research and development of cognitive tools.

_Cognitive Tools for Scientific Inquiry_

As cognitive partners, cognitive tools interact with learners to construct knowledge, bringing their
expertise to the activities; as technological tools, they can be flexibly used for various activities and open
to the mindful growth as a joint system with learners. The important aspects of cognitive tools can be
summarized as below:

- Cognitive tools should bring certain expertise to activities especially for knowledge-based,
  functional and representational elements that can be better facilitated by computer technology:
  this means that learners should perform most of executive functions, such as decision-making and
  higher-order reasoning;
• Cognitive tools should be flexible in their usage, thus applicable by both elementary and advanced learners for various kinds of activities;
• Cognitive tools should promote cognitive (knowledge building) activities that are otherwise impossible or hard to implement without the tools;
• The use of cognitive tools should assume the interdependence between the tools and the learners: the assumption is that certain cognitive activities cannot be performed solely by a person or by a tool;
• In the use of cognitive tools the resulting characteristics of activities, including processes and products of performing tasks, should manifest some characteristics of expertise in the domain;
• And at the same time, there are variations in cognitive processes and outcomes within a joint system as well as among joint systems: the way that a tool is used by a learner changes for different activities, and different learners could use a tool differently within the same activity.

Cognitive Tools with Specific Expertise

The first two of the six aspects are particularly concerned with the design of a tool itself: its flexible roles in performing activities. Tools have their own unique properties so that we can use them for our specific purposes. The perspective of distributed cognition regards tools as conveying some cognition so that we do not have to be smart on everything (Clark, 1994; Seel & Winn, 1997). Tools, then, can be thought of as designed to convey some expertise that they bring into the partnership, especially for tasks that are hard to achieve through the human mind alone. The expertise of a person is developed over time, whereas expertise of a tool is fixed, to be exploited by users. Patel and Groen (1991) categorized human expertise in three levels: domain-independent (general) expertise, generic expertise, and specific expertise. These levels are used here to understand the roles of tools for cognitive partnerships. More specific cognitive tool would afford more particular content area (e.g., genetics manipulation); more general kind would allow various activities and contents (e.g., spreadsheets).

Inquiry-based learning refers to the learning situations that particularly resemble scientists’ inquiry practices of constructing knowledge through questioning the world phenomena (Greeno, Collins,
Focus of cognitive tools in inquiry-based learning is usually not just for gaining scientific knowledge. Knowledge is not only the product of inquiry process but also means for new inquiry. It is not the cognitive tool that provides appropriate knowledge, but it is the learner him or herself that constructs scientific understanding through the process. Cognitive tools are present during the learners’ inquiry to complement the process of their investigations.

Cognitive tools for scientific inquiry should then be characterized by their specific roles as inquiry partners as well as inquiry tools. As partners, cognitive tools should be able to provide their specific expertise for the targeted knowledge domain such as creating visual representations and understanding particular rules in physics to run models; as tools, they should provide means to investigate phenomena such as measuring instruments and observation methods. It is important to recognize their “toolness,” which indicates their flexibility for various activities. To provide students with authentic experience as novice scientists, cognitive tools for learners are developed by modifying real scientist’s tools, redesigning with some partial aspects of them, or newly designing with similar ideas.

One of the projects that have gone through the iterations of research and development is the Learning Through Collaborative Visualization (CoVis) project. CoVis project open-ended inquiry within a constructivist learning environment (Edelson, Pea, & Gomez., 1996). The major component of CoVis is its investigation tools for learners, such as Weather Visualizer and World Watcher for scientific visualizations. Their latest design of WorldWatcher provides two dimensional visualizations of data about climate, physical geography and human activities with geographic referents (e.g., continent overlays and latitude/longitude markings) and constant readouts of the location and the data value (Edelson et al., 1999). The tool provides functional interface for learners to explore the data through visual representations and is open to new data sets for various activities.

For the scientific phenomena that are hard to be observed or researched through direct data collection devices, scientists use the techniques of computer modeling. The modeled phenomena become their major source of data collection for their research. Model-It is a tool for building dynamic models for scientific inquiry for learning in this manner (Metcalf, Krajcik, & Soloway, 2000). Model-It provides
cognitive tools for learners to plan, build, test, and evaluate models of dynamic systems. Model-It can be used for creating various complexity levels of systems, such as stream ecosystems and human body systems, allowing learners to import graphics to contextualize their models and to define factors and relationships among components of a system (Metcalf et al., 2000). Another cognitive tool for flexible use can be exemplified by GenScope, which is specifically for the domain of genetics. GenScope provides six different observational levels (i.e., molecules, chromosomes, cells, organisms, pedigrees, and populations) for genetic descriptions with their representation and manipulation means, which can be flexibly devised or restrained for use depending on the particular levels of learners and activities (Horwitz, 1999; Horwitz & Christie, 2000).

*Learning Activity Promoting Real-World Scientific Investigation*

The aspects listed above are also related to the activities that students become involved in with cognitive tools. The design of cognitive tools and activities for learners should be distinguished from that of other kinds of computers and activities. Cognitive tools are for profound thinking, similar to that of people engaged in real problem-solving situations. Many domains of experts now use computers as a part of their professional activities, varying from organizing and representing their thinking to creating actual products (Ericsson & Smith, 1991; Perkins, 1993). Activities using cognitive tools should convey the usage of similar tools in the world as well as the expertise of the people involved because the design of a tool becomes worthwhile only because of the activities it affords (Salomon, 1993).

Especially in science, important characteristics of experts and their developments can be seen in their usage of tools (diSessa, 1990). Indeed, for scientists, the advancement of knowledge in many scientific domains is now so dependent on computers that computer modeling has become as important as theory construction and experimentation (Pagels, 1988). As the use of computer tools changed the processes and outcomes of activities in the world, tools and activities in the classroom should change to reflect the nature of real world practices.

Scientists construct their knowledge through their specific activities, perhaps using codified knowledge as a resource, but guided by their own inquiries and/or their situational demands. Inquiry-
based pedagogies follow the way experts explore the phenomena in the world to solve problems and find explanations. Activities with cognitive tools for scientific inquiry should reflect the characteristic of scientists’ inquiry practices both in their specificity and in their variability. In the Global Warming Curriculum study of CoVis project, students prepared briefings for a fictitious international conference (Edelson et al., 1999). The processes and products in this approach resemble those of scientists’ practices. Moreover, the way students define their own problems, build relevant models, and construct and evaluate arguments with Model-It software reflects the way scientists interact with their models (Spitulnik et al., 1999). GenScope even employed an approach wherein the scaffolded features of the software can be faded as students progressively improve in their scientific reasoning (Horwitz, 1999).

*New Opportunities as a Joint System of Learning*

The important aspects of cognitive tools are concerned with the novel opportunities that learners can have by working in conjunction with a cognitive tool. As a joint system, the functions of a cognitive tool work only in response to what learners do. In the research of chess expertise by (Charness, 1991), chess expertise was studied with a computer chess game opponent. Expertise of chess player, ranked as grandmaster, international master, master, expert, and so forth, appears as a stable quality of the player. The player’s use of expertise, however, depends largely on what kind of move the computer makes (which depends on the previous move of the player) and what kinds of patterns the player has encountered before; the player even discovers new patterns and strategies as he or she proceeds.

Cognitive tools in the scientific domain often create very unique opportunities for cognitive tasks, such as exploring microscopic or telescopic phenomena that are impossible to observe with human eyes. WorldWatcher, one of the tools from CoVis, allows users to select units, examine visualizations at varying scopes, customize the display of visualization, 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 a tool. The opportunity that a modeling tool provides can be building complex systems that do not necessarily exist in the real world. Learners can not only build models to understand a particular system with factual data
but also answer “what if” questions. Model-It, by allowing learners to define objects and their relationships, provides learners with opportunities to explore hypothetical models (Krajcik et al., 1998; Spitulnik et al., 1999). GenScope also allows learners to alter a gene from one allele to another so that they can discover Mendel’s laws of inheritance by observing the consequences of their manipulations (Horwitz, 1999). In all three cases, tools do not give learners any kind of correct visualizations or models so that learners themselves have to decide what and how to model or visualize and with what values. The cognitive function of these tools is to bridge the space between the decisions of learners and the visual products.

Researching the Joint System of Learning

Our main assumption about the learning situations involving a cognitive tool is that cognition is distributed within the formed joint learning system during learning (Salomon, 1993). Specifically, the learner(s), tool, and activity bring in specific affordances that constitute the expertise of a joint system, and interactions among them build the distributed structure of thinking and working together. The questions of this study to test this assumption and improve the design of the joint learning system are:

1. How are different roles distributed between the learner and the tool for cognitive tasks?
2. What kinds of deficiency or proficiency in their roles cause success or failure of the performance of the joint learning system?

The main concern of methodologies for the research on cognitive tools is how to capture complex relationships and actions. These researches should deal with another dimension of complexity in the context, which makes it harder for researchers to conduct rigorous observations. In addition to the messiness of the real context, research has to account for new additions of technology and the changes that are brought into the learning context due to the adoption of it, such as curriculum and assessment (Kozma, 2000a). The cognitive processes of learners as well as processes of cognitive tools are all entangled with other components of the context, but are not easily revealed to observers.

This study is particularly concerned with a learning situation where a cognitive tool is used for scientific inquiry. Virtual Reality Modeling Project (VRMP) is a reform effort for an undergraduate
astronomy laboratory course at the University of Georgia. The main characteristics of this project include the implementation of modeling-based inquiry (MBI) pedagogical approach and a 3D-model construction tool called Astronomicon to enhance students’ understanding of astronomy, specifically addressing basic topics of orbits, time, phases, eclipses, and seasons.

Data Collection

Data collection methodologies, such as videos, logs of user interactions, and recordings of computer screens, are now incorporated into observations and interviews in order to capture interactions between learners and technology (Barab, Hay, & Yamagata-Lynch, 2001; Goldman-Segall, 1998; Kozma, 2000a). This study has adopted a complex digital data collection and analysis system, called Integrated Temporal Multimedia Data (ITMD) research system (Hay & Kim, in press), for the in-depth investigation of the learning process. With this system, activity within each group, screen captures of computer activity and voices of participants are recorded, stored, and brought together to play simultaneously for analysis. Through this approach, the collected data maintain the richness that is close to the original context, providing access to the detailed interactions among learners and technology. In Figure 2.1, one camera is set-up for each group, and an extra camera is set-up at the back of the classroom to capture activities that happen beyond the group level.

- Insert Figure 2.1 about here -

In addition to the digital video data from the classroom, data were collected from multiple sources in order to gain more complete understanding of the learning process and to triangulate findings. The written reports and some notes taken in class by learners were collected, which showed their understandings about particular tasks. Data from pre and post tests for basic astronomy knowledge were examined to diagnose student conceptions related to the phases of the moon; surveys and interviews were conducted to understand students’ backgrounds, interests, and comfort levels. Informal conversations, as well as email correspondences, frequently engaged the instructor in order to better understand the learners, their activities and underlying concepts, as well as to assess the expectations and concerns of the instructor.
Participating learners were undergraduate students, mostly taking the course to fulfill their requirements; nonetheless, a few were science majors. Most of the students were not aware of this novel lab format before coming to the class. They worked collaboratively in pairs using Astronomicon throughout the semester. Figure 2.1 illustrates the classroom setting with the five participating groups of students. Each group used two laptop computers with wireless internet connections.

Data Analysis

The design of a learning environment is realized differently by the different perceptions of students about technology and their emergent purposes and curiosities (diSessa, 1990). The way that a tool is used by an individual learner changes for different activities, and different learners use a tool differently within the same activity. To understand this variability, the structure of distribution was examined first with one group and then compared with other groups to find the pattern of the distributed structure of the joint learning system (Glaser & Strauss, 1967).

Recent data analysis methodologies focus on the impact of the features of the learning environment on the reasoning and understanding of learners, such as discourse analysis and interaction analysis (Barab et al., 2001; Jordan & Henderson, 1995). In order to understand the contributions of the participants to the performance in this study, we took an analytic approach of seeing the distribution as a set of cognitive functions coming together to perform a task (Pea, 1993). The way that the expertise is deemed to be structured with knowledge, functions, and representations (Anzai, 1991; Patel & Groen, 1991) were applied to examine the contributions of learner(s), cognitive tool, and activity.

For the purpose of this comparison, the first part of the Moon and Phases exercise was chosen, which learners worked on during the 8th and 9th weeks of the semester (Fall 2003), after learners had gained some comfort with the tool and the course. Learners first answered a common inquiry question (What causes lunar phases?) and then one of five other inquiry questions assigned to different groups. An in-depth examination of one target group shaped the initial conceptual relationships, which were compared with other groups, paying special attention to negative and deviant cases to modify and refine them (LeCompte & Preissle, 1993).
Based on the pretest, many of learners were not familiar with the specifics of the Moon phases, such as their sequence and names. On the item asking about the cause of the Moon phases, more than half of the students (8 out of 14, 57%) showed the common misconception that we see different phases of the Moon from the Earth because the Moon moves in and out of the Earth’s shadow.

The group analyzed in-depth was comprised of two participants, Betty and Allen. Betty expressed some interest in astronomy, but showed the misconception of seeing the Earth’s shadow as a cause of the Moon phases in the pre-test. Allen had a great interest in astronomy coming into the class and he read magazines and books about astronomy. Allen seemed to have a proper conception of the cause of the Moon phases. Allen controlled the mouse for modeling, but he was not the dominant driving force of the group. Betty always gave necessary information and checked on the group’s progress as Allen worked on modeling. They also made decisions together on how to observe and which data to collect. The rest of the groups also had one person who performed more or most of the modeling work (see Figure 2.1): Sally (group 2 with Mindy), Kim (group 3 with Wanda), Steve (group 4 with Kevin), and Marcy (group 5 with Alice).

The following accounts first describe the analysis of the designed expertise structure of the tool and the activity for their knowledge, functions and representations. The process of analysis included charting and comparing the structure of distribution among learner(s), tool, and activity for the selected exercise. The results of analysis include the general pattern of the distribution in this particular learning situation (using Astronomicon as a cognitive tool for scientific inquiry in an astronomy lab), and the patterns of how the joint learning systems work: their successes, failures, and compromises as a system.

Tool and Activity Designs

The way cognition is distributed for learning is first determined by the designed tool characteristics that are potentially used by learners, and then by the prepared learning activity within which learners work together with the tool (Pea, 1993). The cognitive tool (Astronomicon) can be regarded as a specific cognitive tool for inquiry in astronomy. Among various technology for inquiry-based approaches, modeling and visualization techniques using virtual reality technology are probably the
latest emerging ones. Modeling and visualizations are now thought to be among the most important tools of scientists and mathematicians for their professional work. Constructing models and creating visualizations by simplifying a phenomenon’s original complexity are the major means of understanding our physical world (Penner, 2001).

In order to understand the potential roles of this cognitive tool and the provided activity, the expertise that Astronomicon and the structure of activity brings forth to inquiry practice is examined using the theory of expertise through three primary elements: knowledge (facts—rules), functions (simple search—higher-order thinking), and representations (concrete—abstract) (Anzai, 1991; Ericsson & Charness, 1994; Patel & Groen, 1991; Perkins, 1993). The following analysis is based on profound understandings about the project and the conceptual framework proposed above in order to investigate this particular learning situation where an innovative cognitive tool is used for scientific inquiry within an inquiry-based pedagogical approach.

Specific Expertise of Astronomicon, a Cognitive Tool for Scientific Inquiry

Astronomicon: Celestial Construction Tool Kit is a computer modeling tool for astronomy learning, especially planetary motion and light. Learners build and simulate their own models of solar systems within a three dimensional (3D) environment (see, Figure 2.2). The models that learners create using Astronomicon can be used not only as surrogates of real world solar systems but also as experimentations of non-existing systems. These tools become powerful learning partners when students build models with underlying principles and dynamically modify them while running and observing them. Learners gain fundamental understanding about the system, through the logic they use for modeling, as well as through the pattern recognition process from the created model (Kozma & Shank, 1998; Penner, 2001).

- Insert Figure 2.2 about here -

The three primary elements of expertise could be easily applied to and found in Astronomicon (Table 2.1). The knowledge embedded in Astronomicon is the underlying physics for relationships among relevant measures (e.g., masses and sizes of objects, distance between objects, and parent-child
relationships). Its functions are the executions of various operations controlled by learners, such as running the models, switching among perspectives, and changing the running speed. Its representations are chiefly isomorphic keeping the ratio of physical values, such as size and distance, and can be complemented with other abstract representations (e.g., orbital disks).

*Insert Table 2.1 about here*

**Knowledge of Astronomicon**

Modeling allows both for creating simpler representations of a complex solar system or planetary phenomenon, and for visualization of representational images or schemes of the system processes (Feurzeig & Roberts, 1999; Penner, 2001). Astronomicon provides both modeling and visualization capabilities for constructing solar systems and visualizing their processes, for which specific underlying rules and realistic cases of astronomy are embodied in the software as knowledge.

In order to assemble appropriate inputs of users, Astronomicon features a modeling input interface corresponding to the necessary information needed for modeling (Figure 2.3). Models are produced by underlying rules for relationships among different parameters, such as mass, diameter, rotation rate, tilt, radius, and orbital period models. Depending on the complexity level of the system, Astronomicon applies physics-based and/or geometric relationships to the model. For example, when applying a physics-based relationship to a Sun-Earth model, the orbital period of the Earth is decided by the distance between them and their masses. On the other hand, when applying a geometric relationship, masses and distances no longer affect the orbital speed, and the user specifies how long it takes for the Earth to orbit the Sun.

*Insert Figure 2.3 about here*

For the models and visualizations in a 3D space, Astronomicon configures and represents the distances, directions, and scales of the model in proportion. Its knowledge about the relationships among time, space, planetary motions, and light are applied to produce proper patterns while running the model and to provide visualizations.
Functions of Astronomicon

Modeling, visualizing and observing are the processes to understand the underlying relationships among different components of the system and the inner workings of certain phenomena (Feurzeig & Roberts, 1999; Penner, 2001). Astronomicon performs important functions of executing rules for modeling and observation processes in working with learners. In changing perspectives, Astronomicon executes rules to configure 3D space and relocate the views. With waypoints, the observation can be oriented from a place, such as front, overhead, center, or surface of a planet in order to watch the planet itself, its satellite(s) and/or other planets. Keeping the proportion of the enormous scale of space often makes it hard to see distant objects. For this, Astronomicon allows for zooming into a focused direction with \(2^n\) increment up to \(2^{20}\) times. In Figure 2.4, the waypoint is set at the above the Sun to look at the Earth, and the view is zoomed in 128 times.

- Insert Figure 2.4 about here -

Representations of Astronomicon

The representations of Astronomicon have unique aspects because of its use of 3D virtual reality technology. Psychologically, virtual reality is an artificial environment created by a computer whose user feels present in it; technologically, it is a set of stationary three dimensional pictures, which moves to the opposite direction of the user’s movement to create an illusion of space (Lanier, 1989; McLellan, 1996). Virtual reality in education provides the perceptual experiences of being present in the virtual environment (e.g., Johnson, Moher, Ohlsson, & Gillingham, 1999; Salzman, Dede, Loftin, & Chen, 1999). Virtual reality as a cognitive tool can be especially valuable where the learner’s movement in the 3D space (i.e., perceptual cognition) can have a significant role in understanding certain concepts.

Astronomicon virtual space creates reality that is much simpler but physically isomorphic to the real system. The software provides realistic textures of our solar system planets and night sky constellations cast on the celestial sphere. Once the models are built and operated, the representations correspond to the phenomena happening within the system. The planetary motions and the effects of
lights (shadows and phases) dynamically change as the planets rotate with their realistic textures and the constellations move across the sky.

Regarding waypoints, Astronomicon provides the representations of modeled realities, which can show a phenomenon from various perspectives beyond the perspective we have from the Earth. This perspective-taking within 3D space by moving from one place to another is most essential in understanding planetary motion and light.

Modeling-Based Inquiry: Learning Activity for a Scientific Investigation

Models are an important tool for scientific inquiry, and forms of models vary depending on the specific concepts investigated. Adopting scientists’ models in education has proven important for research not only vis-a-vis physical models (e.g., Lehrer & Schauble, 2000; Penner, Lehrer, & Schauble, 1998) but also computer models (e.g., Loh et al., 2001; Wu, Krajcik, & Soloway, 2001). Modeling-based inquiry (MBI) (Hay, 2000) is a specific pedagogical approach that focuses on computer modeling to investigate phenomena that are impossible to do without such tools. Modeling-based inquiry with a cognitive tool manifests the practices of experts: it bears the practical concern that scientific knowledge, scientific tool use, and inquiry skills are all intertwined (Edelson et al., 1999). Through MBI, students engage in model-building practices to try out their hypotheses, methods, and strategies using the similar processes of scientists.

The inquiry activities in this lab were designed to directly address common misconceptions on astronomical concepts. Misconceptions about astronomy are common because scientific reality, especially when it is beyond the scope and scale of human observations of the universe, differs from our perceived reality (Comins, 2001). In this particular curriculum for astronomy misconceptions, learners were given questions to investigate along with two or three theories to explain the phenomena, including both accepted and alternative conception theories. A typical inquiry process for MBI for this lab activity included:

1. Start with a question;
2. Plan a model for each theory;
3. Build and validate a model for each theory;
4. Make observations of the model;
5. Make claims and develop arguments;
6. Write a report;
7. Present process and findings.

Learners usually examined one theory and, if any, reviewed relevant instructor’s introduction notes in order to build or modify a model for it. Planning, building, and validating a model were an integrated process. For example, learners often started putting in the Sun and discussing how to make other objects at the same time. After or during watching their model running, they started claiming reasons for what they saw, and made arguments for why they would support one theory over another. In order to collect evidence to support their claims, they collected, shared, and stored the observational data, recording how many days it took for a certain phenomenon to occur, and taking pictures of different views. They usually spent time in the lab observing and collecting data from the model and wrote their reports outside of this lab time. For class presentations, they were asked to talk about how they modeled each theory and to argue which one they would support and why.

*The Inquiry Activity for This Study*

The fourth exercise of the lab, The Moon and Phases, addressed the misconceptions of the Moon phases that are caused by our one-sided interpretations of phenomena based on what we can see from the Earth. This exercise further explored phases of planets, such as Earth, Venus, and Mars. The most common incorrect explanation for the cause of the Moon phases is that they are caused by the Earth’s shadow (Comins, 2001). Other misconceptions about the phases, such that different countries see different phases of the Moon on the same day and that we only see one side of the Moon because it is not rotating, have also been listed by a number of studies (Philips, 1991; Sadler, 1998). All the groups of learners investigated the question, “What causes lunar phases?” in order for them to challenge the most common misconception about the cause of the phases. Each group investigated a different question regarding other misconceptions about the Moon phases and the phases of other planets. The three given
theories for this question were:

a) Phases of the Moon are caused by a shadow from the Earth;

b) Lunar phase are caused by the changing position of the Moon with respect to the Sun;

c) Lunar phases are caused by its own light changing.

Learners built models of Sun-Earth-Moon system to test these theories, the second theory being the correct conception and the others being the alternative ones. To do that, they had to find the fundamental concepts and information to work with and figure out the modeling procedures.

*Conditions for Modeling and Observations of Each Theory*

Learners were expected to compare the models of given theories for their inquiry in terms of the original question. As summarized in Table 2.2, the activity for the inquiry question, “What causes lunar phases?” was carried out with the designed conditions for modeling and observations of each theory.

Using the expertise structure framework, there is knowledge acquired for and constructed through modeling, functions that guide modeling and observations, and representations that are expected to be used to support claims.

- Insert Table 2.2 about here -

The first theory (a. shadow theory), “Phases of the moon are caused by a shadow from the earth,” required students to understand and adopt the concept of an epicycle, which is a planet’s circle whose center at the same time describes a larger one. Epicycles were widely accepted by early astronomers to explain planetary motions (retrograding), which were otherwise inexplicable with the ancient Greek view that the Earth was the center of the universe (Crowe, 1990). The Moon has to make its own orbit instead of orbiting around the Earth to move in and out of the Earth’s shadow in this model. In Figure 2.5, the center of the Moon’s orbit is no longer at the center of the Earth. The orbit of the Moon makes an epicycle by its center staying at the opposite side of the Sun behind the Earth. To explore this theory, learners also had to understand the difference between the orbital period and the time period for a full set of phases as well as to understand the role of the Moon’s radius for its orbit.

- Insert Figure 2.5 about here -
The second theory (b. position theory), “Lunar phases are caused by the changing position of the Moon with respect to the Sun,” reflects the proper conception about the phases of the Moon, so learners need to collect the actual values of the three objects from their usual sources, such as a textbook and information website. To build this model, students engaged in the basic modeling practice of making each object and assigning parent-child relationships among objects. In order to compare this model with other models, they needed to use the same waypoint and collect pictures at comparable phase times.

The last theory (c. dark-side theory), “Lunar phases are caused by its own light changing,” requires building a model whose phases are not affected at all by the Sun’s light. This theory assumes that the Moon has its own dark and light sides so that we see phases as the Moon rotates. The suggested way of modeling this theory was to use a half dark and half light texture. As the Moon makes its own rotation, the shape of the Moon appears to be similar to that of the real Moon phases. Learners had to figure out the rotation rate of the Moon so that they make the model as similar as possible to the real one. Similar to the first theory, the Moon had to stay at the opposite side of the Sun at all times. The moon then stayed in the shadow of the Earth. They also had to use the same waypoint and collect pictures at comparable phase times to compare this model with other models.

The Joint Learning System: Learners, Astronomicon, and Astronomy Lab

The analysis of the designs indicates the potentials for the distributed structure of cognition. The tool and activity finally become parts of a joint learning system when learners come into this specific learning situation. This section describes a general pattern of distribution of a joint learning system in this particular setting. In order to understand the workings of this intellectual partnership, the basic distributed structure of joint learning system, including learners, Astronomicon, and the other set-up of Astronomy lab (the activity and the instructor), is identified with the three primary elements of expertise: knowledge, functions, and representations.

Researchers of distributed cognition suggest that certain properties should not be distributed to technology: higher-order thinking such as problem-solving and pattern recognition, and executive functions such as deciding what to do and where to go (Perkins, 1993). The technology can process rules
to perform tasks, such as producing representations with inputs, tracing user activity, and retrieving information, but cannot understand the meanings of representations and activities (Salomon, 1993). Learners should find base information for investigating the problem situation, make decisions about how to approach the problem and how to create models, and recognize the patterns of phenomena. Astronomicon visualizes bodies with learner’s inputs, runs the model with the underlying rules, and provides various investigation supports. These roles are played out differently depending on the specific question, learners’ knowledge base, and decisions they make during the process.

Table 2.3 describes the overall distributed structure of the joint learning system, and not even one construct from the table can be totally separated from the others. The distributed components, knowledge, functions, and representations originate from each segment to work as a system. The instructor’s guidance and provided materials become the basis for the performance under the activity/instructor column. The designed activity and the instructor provide the intended use the knowledge with questions, theories, relevant concepts, and required information. The functions are the guidance reflected in the activity and provided by the instructor for learners’ inquiry processes, as to how to model certain phenomenon, how and what to observe, and what kinds of data to collect. The representations used for this guidance are the textbook, websites, and exercise sheets that are put out for learners. Another form of representation by the instructor is the notes that he often writes on the board during his talks. For example, he draws a diagram of a system on the board in order to explain how to make a model with an epicycle of the Moon for the first theory, similar to Figure 2.6.

- Insert Table 2.3 and Figure 2.6 about here -

For the learners’ part, knowledge, functions, and representations of the two learners working together are treated as one and not separated from each other in the table. Learners have some knowledge about relevant astronomy content and basic rules, such as doubling a radius value to acquire its diameter value. Many learners have their prior conceptions about ordinary phenomena, such as phases and seasons, which sometimes are incorrect. Their prior knowledge as well as any collected information from textbook, website, instructor and even from their existing models become the background for their activities. In
addition to the knowledge about astronomical concepts and how to use Astronomicon, learners gain knowledge about the process of modeling and observations. This includes their understanding of the spatial relationship among created objects within 3D environment, of visualizations and perspectives to use to better find evidence, and of pictures to take to support their claims.

The functions of learners are related especially to their decision-makings throughout the MBI process. These functions affect how the software is used and how the activity is carried out, and at the same time, they are affected by the design of the software and the activity. Consistent with phases of the MBI process, learners examine each theory, make models and validate them, make observations, and start making claims of why they see what they see. They decide on what to do working with the model, what values to input, what features to use, and what waypoints they make and use. During their fourth phase of MBI process, they observe the created model, recognizing its patterns. They also try matching their observations with their astronomy knowledge, such as the name of a moon phase. Toward the conclusion of their MBI process, learners collect evidence for their claims, that is, picture from the model.

The representations of learners tell us what kinds of knowledge is used and constructed, how they performed their inquiry, and how they represent their understandings. The learners’ representations include their written notes with drawings and records, and exercise reports. The collected data in their reports include the screen captures of views that can support their claims and the numeral data to explain the inner workings of the model, such as how many days it took for the Moon to orbit the Earth based on their observations. Their collections of screen captures and the written reports reveal their understandings about the tasks and their solutions and how they organize their understanding to present to others as a report.

Astronomicon, as explained above in detail, embodies knowledge, functions, and representations that extend the capabilities of the learners. It needs to operate its embodied rules with the learner inputs in order to create representations of testing phenomena. This complex joint learning system including learners, Astronomicon, and the astronomy lab, makes it possible to engage in deeper inquiry into astronomical phenomena. The general pattern of distribution helps us to see how this joint system of
learning operates within the conditioned inquiry activity. The next section demonstrates how this overall distribution pattern plays out for the inquiry question, “What causes lunar phase,” and how the successes and mistakes in performances are made as a system.

The Joint Learning System Working

Beginning the Moon and phases exercise, the instructor explained how to build models for the three theories. The details of how to build these models have been discussed earlier. He drew a diagram similar to Figure 2.6 on the white board to describe the epicycle for the shadow theory. He recommended using circular orbits, with which the model depends only on the geometric relationships among objects. The way that learners interacted with Astronomicon became conditioned by the given activity and the instructor’s orientation.

All the groups started their activity with modeling of the shadow theory (a). After that, some groups worked on the position theory (b) and then the dark-side theory (c) in order. Others, however, decided to work on the third theory before the second for two reasons: first, the shadow model (a) could be easily modified to create the dark-side model (c); and second, they could make the incorrect ones first and compare with the real, position theory model (b). The typical process of working on each theory corresponded to the MBI process. In planning the model, learners reviewed the theory and the explanation of the instruction, often referring to the diagram on the board during their conversations. The modeling of the first theory took quite a long time as they needed to figure out the radius and period of the Moon’s orbit around the center point, which the instructor called point M (see, Figure 2.6). The modeling of the other theories was relatively short, but some groups spent a longer time because their decision to modify an existing model forced them to verify various inputs, which turned out to be inappropriate for their current model. The student observations focused on the changes in the phases as suggested by the instructor. As the learners moved from one model to another, they started comparing their observations among the phase patterns of the models, claiming reasons to approve or disapprove each theory, and collecting pictures of different phases as evidence for their reports.
As a cognitive tool for scientific inquiry, Astronomicon provides unique thinking and learning opportunities that are impossible without it. These opportunities are better actualized when used with realistic scientific activities, and are influenced by the others participate together in them. Through this study, we examined how this unique learning experience become possible and distributed as a joint learning system. We found the pattern of each group struggling to overcome their naïve scientism, which sometimes was successful and sometimes not. We also found some variations on the way each group performs their tasks apart from their success or failure. These findings are organized into four overarching themes below: unique opportunities as a joint system, system of naïveté, power of the joint learning system, and influences on variations.

**Unique Opportunities as a Joint System: Modeling Misconceptions**

One of the unique opportunities of this activity with Astronomicon is building the models with misconceptions that are impossible in the real world. In order to address the misconception that the Moon phases are cause by the shadow, Comins (2001) explains the same model with an epicycle of the Moon through a narrative and an illustration. He explains the set-up of geometry among Sun, Earth and Moon where the Moon and the Sun always stay on the opposite sides of the Earth. According to his argument, this geometry is not possible in the real world because the Moon would fall onto the Earth surface by the gravitational force if it stays on the opposite side instead of orbiting the Earth. The activity with this theory requires capabilities to build a model only with geometric relationships without the effects of gravitational forces created by masses of and distances among objects. Using Astronomicon, learners are actually given an opportunity to model the phenomenon in order to help them realize how unrealistic it is (see Figures 6 and 7). This opportunity was actualized by some groups as joint learning systems.

Table 2.4 summarizes how the modeling of the epicycle of the moon was performed together as a joint system. The number in each parenthesis is the typical sequence of operations observed across groups. Learners started their modeling by reviewing the information from the instructor (Table 2.4, #1). As suggested by the instructor, most of them made the model from scratch. Once opening the input window, learners started looking for necessary information using the textbook or web resource (#2 & #3).
Learners doubled the radius value because those resources only gave the radius of each body and Astronomicon required input of diameter (#4). Making the Earth, they made the Sun its parent with a circular orbit (#4.1). Creating the center point (point M) of the Moon’s orbit, many started to look back and forth between their screens and the epicycle drawing on the board. They inserted 365 days for its orbital period so that it would always stay inline with the Earth, directly opposite side of the Sun (#4.2). For the Moon, they inserted its actual size and mass, which do not affect the relationship with other objects. Most of them randomly assigned its distance from the point M, but at least tried to make it smaller than the distance between the Earth and the point M (#4.3).

With the inputs from learners, Astronomicon applied the geometric relationship to the created system, which was configured with the distances, directions, periods, and circular orbits (#5). Whenever an object was created, it was selected and indicated with the blue tracker displaying its name and distance from the view point (#6, #7 & #8). Learners often switched waypoints during the model building, such as to an overhead view, to make sure that the objects are appropriately created and aligned (#9 - #13).

Learners then started observing their models from a view where they could test and check the orbit of the Moon (#14 & #15). Learners ran the system when zoomed in to a comfortable observation level (#16 & #17). Astronomicon executed the complex rules for planetary motion and light within the created space and the running time. The created view showed the point M always staying behind the Earth, and the Moon moving in and out of the Earth’s shadow (#18 & #19). Most of the learners first made the size of the Moon’s orbit much larger than the shadowed area so that the Moon was in full phase for many days in a month. Recognizing that the Moon was out of shadow for too long compared to its time in the shadow, they made the radius of the Moon shorter (#20 & #21). Astronomicon reapplied the geometric relationship to the model every time they changed the value, so how long it stayed in the light and in the shadow changed according to the changed orbit size (#22). Learners repeated this process until they found the correct size, where the Moon just slightly touched the shadow when it was on either far side of the shadow (#23, #24 & #25).
No knowledge, function, or representation in this process worked independently of others. The goal of modeling this misconception, however, constituted a distributed cognitive process that required a profound understanding of underlying relationships and lead into the goal of comparing with other modeled theories. This unique modeling opportunity, however, was not always apparent to learners. The chance to model the misconceptions sometimes received as the main goal of their activity instead of as the process of coming to a conclusion for a proper theory. As a result, some of the groups would focus only on reporting how they built the model and how it worked rather than observe patterns that differentiated from other models. Mindy and Sally (Group 3) had this problem with this particular activity. They finished modeling the shadow theory with the Moon epicycles and were about to observe the phases:

1. [Sally adds a new waypoint from the Earth to the point M.]
2. Mindy: [reading from the exercise sheet] ...phases of the moon are caused by the earth…
   [glimpsing at the screen] So basically, what do we have to see in order to prove that the phases of the moon are cause by the shadow from the earth… [looking at Sally]. Are we supposed to see the different phases of the moon? Is that what we have to...?
3. Sally: [picking up and reading her exercise sheet] …the phases of the moon are caused by the shadow from the earth… [looking up the screen] …and what we will say is [pointing at the screen with the point M overlapping with the Moon] that point M is directly behind the earth so it’s always in the shadow. So then we will take pictures of new moon going in and out of the shadow [making her right hand flat and pointing toward the screen and moving to the right and to the left], that is cause by the earth... so that’s pretty much... [looking at Mindy]
4. Mindy: So that’s how we prove the phases...?
5. Sally: Oh, what we are trying to do is to make a model that looks like this, that may not be the reality... then later on we have to go back and say... that’s not really how it is.
6. Mindy: Ah... See, I don’t know why we don’t get to make the reality one, why we always have to fake it.
Mindy tried to figure out what they needed to look for from the model [2]. Sally, however, was focused on the workings of the model and explained to Mindy how the model worked [3]. As an answer to Mindy’s question regarding the evidence to prove (although they need to disprove) this model, Sally gave the workings of the model itself as the evidence for disproof [4-5].

*System of Naïve Scientism*

The claims that learners made to prove or disprove a theory at the beginning of the exercise were often unacceptable due to their naïve inferences based on their common senses. Drawing conclusions about scientific phenomena based on our personal experiences or insufficient evidence from experiments often leads to a mistake (Comins, 2001). Most of the learners attempted to draw a conclusion only after observing the first model once, defeating the purpose of testing three theories to explain a phenomenon.

As a joint system, a person making a claim is not solely responsible for mistakes. The joint learning system as a whole contributes to the naïveté of scientific inquiry. Table 2.5 summarizes the two cases of naïve scientism that happened during this activity. The examples are marked with letters A and B to indicate the different paths of the two problems: A. claims with irrelevant data; and B. claims based on common sense.

- Insert Table 2.5 about here -

*A. Claims with Irrelevant Data*

During this activity, learners made mistakes of seeking irrelevant evidence from their models. Modeling a theory requires incorporating the real observational data into the model as much as possible. For the shadow theory model, for example, a well-finished model would take about 29.5 days (synodic period) to go through a full set of phases by the Earth’s shadow.

The problem situations occurred in this case by learners’ inputting an inappropriate value for the orbital period of the Moon, thus missing the instructor’s hint that they needed to figure out the Moon orbital period so that it would correspond to the actual time it takes to go through two full sets of phases (Table 2.5, #A-1 & #A-2). Group 1 (Betty and Allen) and group 3 (Wanda and Kim) showed a similar mistake of focusing on the discrepancy in the synodic periods which were set by their input.
Betty wrote down on her note and talked with Allen about figuring out the Moon period, but it did not last on their minds. Allen put in 27 days into orbital period box, remembering the number from his previous work (#A-2). Wanda and Kim, on the other hand, decided to test the model first before figuring out and changing the Moon’s orbital period from its default value, 1, and forgot to change it. We can see the contribution of the design of this activity to what happens here: although the orbital period of the Moon is not one of the most important characteristics to think about in order to compare the shadow theory to others, students needed to deal with it to make a complete model.

Astronomicon exhibited the modeled pattern accounting for all the input variables, including day counts and planetary motion and light according to its geometric locations and relationships (#A-3 & #A-4). The Moon started dark in the shadow, then the shadow moved away to the right and came back to cover it up again, and then it moved away to the left and came back to the center (#A-5). This opened up an opportunity for learners to think and understand about the difference between the phase period of the shadow model and that of the real one, but also left the possibility of turning their attention away from other important characteristics.

In the course of seeking evidence to disprove the theory, these two groups first did not find evidence from the phases and decided that their shadow theory model could be disproved because of its wrong synodic period (#A-6, 7, 8, & 9). Betty tried to attend to the pattern it created in order to understand how this model worked to go through phases (#A-6). They observed its change of phase from new, to half, and to full, but did not attend to the phase shapes in-between. Figure 2.7 includes the screen captures from the reports of Betty and Allen: The shadow was about to cover up the entire Moon as it moved into the Earth’s umbra (left to right). Betty started to understand how the model worked by watching the model running [7-10]:

7. [The Earth’s shadow is covering half of the Moon, gradually revealing the entire face, and covering it again.]

8. Betty: [watching the Moon] so now... it was half moon, and now went out to a full moon, and then back into...okay...
9. Allen: [pointing to the screen] cause it came back and went out, we took a picture of half moon, and it kept going, that’s this full moon and going to cross back, that’s going to be another half moon, and it will be new. Allen: I guess we can take picture of the new moon at the beginning point... [running the model and stopping where point M is aligned with the Moon] right there (Figure 2.7, right).

10. [Allen continues on running the model and taking pictures as Betty writes notes about their observations]

- Insert Figure 2.7 about here -

While writing notes, Betty talked about how their observations could disprove this theory and realized that the phases they captured were actually very similar to the real ones. She then recognized that it only took about 29 days to go through 2 sets of full phases (#A-7) [11]:

11. Betty: [looking at her notes] I don't know how we are supposed to say like why that can't be right cause they all look... [looking up the screen and the timer reads 29.359381 days] Oh, because... in a month you only see, ’cause that took 29 days to go through all those phases, and that can't be right because in a month, you only see one of each phase.

12. Allen: [nodding his head] yeah…

13. [Allen finishes taking the picture as Betty writes notes about what she just said]

Betty made the claim that the current model could be disproved by the improper time it took to go through the phases, and Allen agreed on it (#A-8 & #A-9) [11-13]. The difference between the pattern generated with underlying factors (mass and distance) and one with direct input (orbital period) was not apparent to the learners. Here is the learners’ contribution to the mistake: their tendency for hurried judgments only with seeming evidence without careful observations and contemplations. Learners should have validated their models before moving onto finding evidence to support their claims.

B. Claims Based on Their Common Senses

Comparing the way phases look among different models, learners often relied on their common senses or inaccurate images of real phases and focused on trivial surface features. The broken realism of
Astronomicon as a factor for naïve scientism is relevant to this common sense problem. The clear line between dark and light in the dark-side theory model comes from the modified texture of the moon, which no longer gives a realistic view of phases (Table 2.5, #B-1). With the goal and the expectations in mind that the phases among theories will look different, learners start searching for differences without being grounded in the evidence, such as the unrealistic look of the phases (#B-2, #B-3, & #B-4). The realism that Astronomicon established up to this point was broken here by having the unrealistically clear separate boundary (#B-5). Even though “the realistic look” does not characterize the phases of the Moon, learners saw it as an important aspect because it was a prominent difference they saw among models in search of the evidence (#B-6 & #B-7).

Kevin and Steve (Group 5) moved onto the last model (dark-side theory) after the first one (shadow theory). Without building and observing the real model (position theory), they decided that the gibbous phases of the dark-side model were wrong because of their shapes. Kevin asked Steve to pause at a gibbous phase (as in Figure 2.8, left) and said, “The Moon looks never like that from the Earth. It should be concave in instead of concave out.” Their judgment was based on their inaccurate memory instead of being grounded on the data from the model (#B-6 & #B-7). Unlike the shadow theory, one of the dark-side theory’s breakdown points is on its observable sides of the Moon. Compared to the real one, the gibbous phase of this model has a similar shape, but showing a different side of the Moon (Figure 2.8). It was not until observing the position theory model that Kevin and Steve realized that the shape itself was not much different.

- Insert Figure 2.8 about here –

Betty and Allen, on the other hand, continued on to the second model with the position theory, keeping their focus on its synodic period, and captured new, half, and full moons as they did for the first model, confirming that this second model had only one of each phase in 29 days. Betty, however, realized that they needed to compare the phases (#B-2) and tried to do it with the phases pictures they had taken so far [14-16]:

14. Betty: [looking up to screen] I thought we were supposed to compare the way different phases look. I mean I guess we will see, it looks different because it was fuzzier, you know...? [looking at Allen] Did you see that? Where in other ones, it was straighter on … with the shadow of the earth? You know what I am saying?

15. Allen: [-leaning toward the computer and holding the mouse] I wasn’t paying attention that close.

16. Betty: Okay, because he just said to look, to compare the two, say, the way the different phases look. Like the way the full moon looks here and the full moon looks there, and the way that half moon looks here and the way that half moon looks there... I guess the full moon and new moon are going to look the same. So the half moon is what we need to look. Or they are supposed to look different. Well, I guess they are going to look different.

Betty, in order to find the difference between the half phases from the two models (#B-3 & #B-4), turns her attention to a subtle difference in a minor surface feature, the fuzziness of the border between light and dark parts [14-16] (#B-6 & #B-7). Group 3 and group 5 also made similar claims that the clear line of a phase made the model unreal, especially when they were observing the dark-side theory model with light and dark texture (#B-1, #B-5, & #B-7). Similar to the A cases, learners claimed the differences in patterns too early without focused observations and comparisons. The potential for this mistake was provided by Astronomicon because it does display the subtle differences in those surface features, and then fulfilled by learners by focusing on them.

Overcoming Naïveté

The cognitive tasks described above are distributed across participants of this joint learning system as described above with two main cases (A and B), which initially formed a system of naïve scientism. The activity structure, learners, and tool all contributed to the problem situation. Those initial mistakes could only be made with this particular Astronomy lab approach with Astronomicon as a collective learning system.
Even though the main decisions were always left to the learners, the overcoming of this naïveté was also the responsibility of the joint learning system. Their claims were challenged by finding phenomena different from their expectations, by the interactions with their partners and the instructor, and by their own conscious effort toward scientific inquiry. In return, learners came to realize that their claims were premature and had a notable learning experience when they started comparing and noticing the differences among models.

Kevin and Steve’s claim that the dark-side theory model was faulty because of the concave-out gibbous phases was challenged when they started observing the position theory model and did not find any difference in the phase shape (Figure 2.8). Betty’s claim of the fuzziness of the half moon lines as a differentiating factor among models was challenged by her partner Allen’s disagreement. These challenges required these students to reinvestigate the phenomena in order to resolve these conflicts.

Most of the learners turned down their premature conclusions, but some learners never broke out of their naïve scientism because their faulty claims were never challenged. Mindy and Sally, unfortunately, never focused their activity on comparing phases among the models. They instead compared each model to their common sense mental image of phases. A disjoint among participants of this group is indicated: The goal to compare phases among three theories was missing in their work; they were less dependent on the evidence from Astronomicon, but more on their unsupported common sense. In her discussion about the dark-side theory model in the report, Sally based her evidence on the unnatural look of the Moon and the theory itself:

“The half Moon shown in the image on the right is caused by half of the Moon’s dark and light surfaces facing the Earth. The phases of the Moon look extremely unnatural in this model. The phases are abnormally geometric and look very fake. In reality, when we observe the phases of the Moon, they look nothing like this. Plus, the Moon has no light of its own. The light we see from the Moon is a reflection of the light from the Sun. Therefore, this model does not demonstrate the real lunar phases.”
The above statement shows that Sally knew which theory was the correct one. However, Mindy and Sally are two of the few people whose post-test results showed that they still held onto the initial misconception that lunar phases are caused by the shadow from the Earth.

_Toward a Powerful Joint Learning System_

Strangely enough, the disjoint of the joint learning system with group 3 (Mindy and Sally) was not apparent at first. The distributed structure of their group was almost identical to the structure outlined in Table 2.4. The mystery of the powerful joint learning system was in something even harder to examine than cognitive process revealed through learners’ conversations and actions. As one of the important properties of learners within the joint learning system, Perkins (1993) discusses higher-order thinking including problem-solving and pattern recognition. The missing link to the powerful learning system for some learners may come from their lack of perceptual attentiveness to recognizing patterns. While collecting pictures for their reports, Sally said to Mindy, “I’m just taking pictures of, like everything,” and gave each picture a name in a numeric order, such as 2A 1 and 2A 2, which does not characterize the picture itself. Each picture they collected did not seem to carry any purpose or meaning for them, thus implying that no pattern was recognized. Three of the five groups recorded their observations for each picture and/or the day-counts in the timer, gave it a name that characterized it, and tried to find a comparable point in other models.

The following example of Betty and Allen is continued from the Betty’s claim on the fuzziness of phases. Here, we see that the joint learning system finally became powerful when learners found the missing link between the model and their observations. Betty raised her hand to ask instructor about seeing differences between first two models because Allen did not see any differences that she saw [17-18]:

17. Instructor: [walking toward Betty and Allen] Yes.

18. Betty: I think maybe I was just looking at the wrong difference. We took a picture of half moon when it was passing earth shadow, when that was causing half moon, and we just took it from the real...
19. Instructor: Between A and B? Well, I don’t necessarily see the difference between half and half, other than maybe which half is light and which half is dark, probably better to see than full or new moon. But what if you looked in-between, say, half and the new, and in-between the half and the full. That’s where true differences come into play.

20. Betty: Because in the earth shadow, it’s not as rounded? Is it the other one? I don’t know that’s what it looks like to me.

Betty almost had it when the instructor talked about in-between phases [19-20], but he continued on elaborating the differences in shapes by using an analogy of rounded donuts and bites [21-23].

21. Instructor: …think of it this way. The moon is in donut, a rounded donut, right? As it moves into the earth shadow, the earth shadow is circular, right? Which means its going to look like somebody took a bite out of that donut. But do actual phases look like that? I mean do you ever get phase where the moon looks like a donut with a bite out of it?

22. Allen: I guess not...

23. Instructor: No, you can get the crescent which got a huge bite out of it. But not a little bite out of the side.

24. Allen: Ah~! [nodding his head]

25. [Betty is watching and listening to the instructor without any reaction.]

26. Instructor: What you end up in reality are a couple of crescents. In this case, you never get that crescent coming in, as you go from a full, back, and your gibbous phases are all messed up. So take a look at just half is harder to tell the difference. I would go to somewhere in-between to get a good picture.

27. [Instructor leaves.]


The instructor’s analogy and his comment on messed up gibbous phases might have confused Betty even more, because following his explanations requires clear mental imagery of the shadow model [25-26]. Even though the instructor did not make her understand, he provided important guidance for them to
attend to particular parts [26] (Table 2.6, #1 & #2). Betty and Allen then decided to delete all the pictures and start over (#3 & #4). Table 2.6 summarizes the following process of reexamining the models and understanding the difference with the changed focus (#5-#15):

29. Betty: [looking at the screen] I don’t know… I don’t really understand.

30. [Allen runs and checks on the waning crescent of the real model, and then opens the shadow theory model. He chooses the waypoint, earth to moon.]

31. Betty: Is this one with point M?

32. Allen: Yeah. [running the model]

33. [The shadow moves to the right and then to the left pretty fast.]

34. Betty: Oh, I see it! [getting up and pointing to the screen] Because that right there is like that instead of like that [making half circle clockwise then counterclockwise]… Yeah, it is curved out instead of curved in!

- Insert Table 2.6 about here -

Betty expressed her confusion restarting the observation for the first model [29], but she recognized the difference immediately after observing the Moon moving in and out of the shadow [33-34] (#13-#14). The revealed pattern from the model acted much more powerfully than the instructor’s description.

The interesting point here is that they had observed the same model, using the same waypoint and a similar process. The phases in-between half and full or half and new that they now decided to focus on were always there, but never recognized. The process and the structure of this joint learning system did not change, but the power of it was brought out with their perceptual attention to the unrecognized parts.

The important differences made to the joint learning system were the elaborated guidance by the instructor for the observation and the corresponding improvement on the learners’ role in pattern recognition, which is a primary higher-order thinking process. There was no change in the role of the tool, but learners’ comparisons were no longer based on their commonsense but on their observations from the models.
Influences on Variations

Each participant in this distributed system of thinking and learning constantly influenced each other’s roles for performances. For this reason, the way that a joint learning system works on a task could diverge quickly with a small change in decision-makings. For each theory, the instructor conveyed a way to build its model to facilitate the process. Although most of the learners intended to make the model exactly like the instructor suggested, the variations among groups happened from decisions learners made at various points. By making a model slightly different from others, the supporting evidence collected from the model became significantly different. In these cases, the role of the learners and the operation of Astronomicon did not change much, but the representations created by Astronomicon and the data collected from it were noticeably unique.

An interesting case occurred with Alice and Marcy (Group 8) when they worked on the shadow theory model (Table 2.7). Sometime after the learners started modeling this first theory, instructor gave a hint for the distance of the Moon from the point M (Table 2.7, #1): “My initial guess for the radius of the Moon orbiting around that point M is 4 or 5 times of the Moon’s diameter….” Most of the groups started calculating the value and changed the radius of the Moon. Marcy, who was dominant in the group, however, misunderstood his suggestion: she got the idea of 4 or 5 times of the Moon diameter, but applied it to the wrong subject (#2). For the Moon radius around the point M, she tested with random numbers instead of calculating it as suggested [35-36]:

35. Alice: We can try… like 14,000 because he said it is 4 or 5 times of the diameter.

36. Marcy: [keeping changing the radius and checking the closeness of the Moon to the Earth’s umbra] Oh, he was talking about the diameter of the point M.

Marcy’s misunderstanding that they should change the diameter of the point M led to an intriguing divergence. After several changes of the radius value, they were satisfied with 10,000. Marcy then changed the diameter value of point M [37-38] (#3-#4):
37. [Marcy adds a waypoint from the Earth to the Moon. On the screen the Moon and the point M are side by side with the same diameter.]

38. Marcy: [opening the edit window of the point M] It (the point M) is not bigger than the Moon [changing the diameter of the point M to 14500].

39. Marcy: Oh, it’s really big… [running the model] but it shows where the shadow goes…

40. Alice: [watching the model] How about if we make the point M really small, like 1? I wonder what phases would look like without it.

41. Marcy: Then we cannot see where the shadow is.

When they ran the model, point M showed where the shadow was [39] (#5-#10). Figure 2.9 is one of the screen captures that Alice and Marcy used in their reports.

Marcy’s decision on making the point M bigger than the moon made their observation process and their collected picture very unique. The point M (which is not a point anymore) was always directly opposite the Sun from the Earth so it was always in the shadow when it was smaller than the size of the Earth’s shadow. In Figure 2.9, the size of the point M is little bit bigger than the Earth’s shadow, so the dark inner circle represents the shadow from the Earth cast on it at all times. The Moon is moving out of the shadow after moving across the shadowed area.

- Insert Figure 2.9 about here -

The role of this novel observational method becomes clear when we compare the observations without it. In Figure 2.7, we can only see the shadow cast on the Moon, which is only a small portion of the shadow overlapping with the Moon, and the rest of the circle is assumed to be somewhere in that range of the distance between point M and the Moon. With Marcy’s incidental input of its diameter, point M became a helpful visual aid in addition to its role as an anchor for the Moon epicycle. The interesting point is that the diameter of the point M was originally a useless value to input, and many learners made it very small so that they would not see it.
Enhancing the Design of the Joint Learning System

The proposed framework in this article helps revealing the interwoven relationships within the joint learning system, in which each participant (learners, tool, and activity) influences and is influenced by each other’s performances. This research study attempted to depict what this distributed learning system actually looks like and how it operates within modeling-based inquiry pedagogy. As demonstrated throughout the examples, how a joint learning system works cannot be understood without examining the distributed roles of each.

The process of Astronomicon, inseparable from that of learners, was limited to model operations and representations because constructing knowledge, such as understanding of the inner-workings with mass and distance and the patterns of a model, was solely up to the learners. The instructor, on the other hand, provided base knowledge, and practical guidance for modeling and observations, but did not take over the learners’ property of claiming and constructing knowledge.

In the previous section, how the unique opportunities were realized by the joint system, how learners fell into and overcame naïve scientism, how the joint system became powerful or remained powerless, and how the variations on their activities were caused by small incidences were discussed and exemplified in detail. Some of the issues mentioned in the discussions need to be addressed further in order to find the fundamental causes and solutions of the identified problems and the possibilities of the current designs.

Tool Design That Promotes Conscious Model-Building

Model-building can be focused on the model’s closeness to surface features of the real system and/or on the processes underlying the system (Penner, 2000-2001). Learners often made mistakes of not being careful of their model inputs during this activity. Having an incomplete model is not a big problem as long as learners understand the underlying process and its incompleteness. Certain values are sometimes not very critical to their performances depending on what kind of model they create (e.g., mass does not affect the relationship between two objects when building geometric model) and what kind of observational data they need from the model (e.g., orbital period of the moon epicycle does not affect the
visual pattern). Some learners had problems because they recklessly made their models without understanding how some patterns were created through their inputs.

This careless model-building is often found in places where learners proceed too quickly. Oftentimes they inserted a value (e.g., orbital period or radius) into a wrong box (e.g., rotation rate or offset distance), were precise in an irrelevant input (mass for geometric model), or forgot to input a value that characterized the object (geometric model Moon orbital period). It is important to make the model-building process a more conscious effort beyond merely copying numbers from a textbook, so that learners better understand the inner-workings of the real phenomena and avoid the risk of making premature conclusions with irrelevant data.

To enhance the system to become more conscious, we could make some adjustments to the tool design. One of the reasons that learners are less cognizant of the effect of their inputs on the model patterns is that there is a separation between the modeling space and the input interface. The current version of Astronomicon has no interface support to dynamically see the relationship between input values and the working of the model. As seen in Figure 2.3, learners no longer see the values they put into the model once they start running it, and in order to check the values they need to stop and open the input window again. Having a window that can stay and allow for modifications during observation would make the complicated modeling and underlying relationships much more transparent to the learners.

**Activity Design to Make Modeling as a Transitive Goal**

Another issue is learners’ perceptions about the purpose of an activity. Learners were told that the exercise was intended to test and compare given theories to prove one of them. However, while being too focused on the process of model building, some learners did not move beyond modeling each theory to gaining deeper understandings of the target concepts. The modeling itself should be a transitive goal, which carries a higher-level purpose of finding patterns and constructing meanings. diSessa (1990) suggested that we should make a distinction between a tool and the domain to be learned, so that one is not mistaken for the other. How to make this distinction explicit to learners is the main task to deal with for the design of activities.
What was missing in the current activity might be a more elaborate planning stage before making the model. Perhaps giving learners a chance to build a blueprint of the computer model with a diagram on paper (similar to Figure 2.5 and 2.7) and to predict what they will see during their observations would help with their understanding. In this way, learners could perceive modeling (whether on paper or in computer) as a tool to explore the concepts, not as the final goal, and could have a clear focus during their observations.

One of the most important issues in forming a powerful joint learning system was the learners’ role of recognizing patterns. Learners were not able to recognize an important pattern during their first observation of the model, but they became able to see patterns after finding the focus for their observations. In the activity of this study, the observable patterns of the Moon phases in the sky included the shapes of phases, the sequence of phases, the unchanging face of the Moon and their associated data, such as time record (e.g., seeing a first half moon around the 7.5 day). If the learners made predictions of these patterns for each model during their planning stage, they could focus their attention on the important aspects. They would also better understand the uniqueness of this opportunity to model the phenomena as they witness the evidence to support or decline their suppositions.

Extending the Joint Learning System to a Community of Scientists

An issue related to naïve scientism was learners’ reasoning though their common senses. Comins (2001) also indicated that drawing conclusions relying on our personal experiences are the main cause of having misconceptions. During this activity, many learners were able to overcome their naïveté when their faulty claims were challenged by other participants of the joint learning system: their claims did not fit into the purpose of the activity; Astronomicon showed something different from their expectations; or their partner did not agree with the claims. As indicated above, having clear expectations from the planning activity can keep learners from making spontaneous connections with their commonsense.

Another thing to consider is to build in some opportunities to be challenged in their activities. The intention of using Astronomicon within modeling based-inquiry pedagogy is to have activities that manifest the practices of experts including working with other scientists (Edelson et al., 1999). Assuming
their roles as scientists is not always easy for learners, especially when they depend on the guidance of the instructor and see him as a primary source of knowledge. By design, we could encourage learners to challenge each other’s claims as a fellow scientist, which is one of the important aspects of scientific inquiry.

Some variations on how they work out different parts of the activity were found across different groups. Alice and Marcy found a novel and very useful observation method, which could have been shared with other groups. From the current account of this study, the variations were taking place incidentally through a minor mistake or misunderstandings. Cognitive tools should be designed to be flexible, providing learners with opportunities to be mindful and creative in their activities (Jonassen & Reeves, 1996; Salomon, Perkins, & Globerson, 1991). Astonomicon does have many possibilities and flexibilities for creative variations as a cognitive tool. These variations should be encouraged by opening the way that activities are carried out for the learners: less attention on teaching how to build each model and more attention on discussion and guidance for overall inquiry planning. It would be beneficial to share what each group comes up with, so they can learn from others’ experiences.

**Research and Development on the Joint Learning System**

The possible enhancements discussed above are mostly related to the changes that we could make to improve the functions of the activity and the tool. At the same time, these modifications of the design in the end will enhance the functions of the learners to model and observe, resulting in a much stronger joint system of learning. This applies to any design effort for inquiry-based learning with a scientific cognitive tool that provides opportunities to build and/or modify some kind of system: The tool should be designed to better support learners modeling building process to understand the underlying relationships; the activity should be designed to help learners focus on their inquiry; and their intellectual understandings should be challenged and treated as those of scientists as a community.

In term of the design of the tool, its structure of expertise was first examined in order to understand the potentials of the tool in this study. This would be useful not only to examine what is used, not used, and needed for improvement for an existing tool, but also to design a new cognitive tool for
learning. The future research and development should be focused on how we should make decisions on the tool designs, considering the trade-offs of supporting certain activities over others. For example, when Astronomicon did not have the embedded knowledge about geometric relationships making the Moon stay directly behind the Earth was much harder because it required dealing with Kepler’s third law, whereas all learners needed with the current version was to make the orbital period of the Moon 365 days using geometric relationships. Using this function to easily make the model they wanted, learners could explore other concepts, but at the same time they lost their chance to better understand Kepler’s third law.

Activities with a cognitive tool are critical assets of the joint learning system. The contributions of research on these accompanying activities are the understandings of what aspects of the activities are facilitating or constraining scientific inquiry, implying what needs to be done for improvements. The future research and development activities should include the possibilities beyond the computer lab, so that learners can experience and connect with what goes on in the real world, such as real astronomical phenomena happening at the present time.

In order to understand the designs of the tool and the activities and how the joint learning system works, the research should examine them with learners together as a system: how the tool and the learner(s) work together, what really works and does not, what lacks from the part of the learners, tool, activity or guidance, and how they can be accommodated through the design improvements of the system. Through this examination, the importance of each participant’s roles and how the joint learning system becomes strong, creative, or weak are revealed. The future research and development on this type of joint learning system may need to address the significance and/or risks of trial-error approaches that learners typically use in order to minimize risks and maximize benefits when working as a system.

Overture

“Put yourself on the Moon for a moment. Choose a nice spot with the Earth high in the sky. Let’s make it sunrise… Set up a camp and watch the Earth and Sun…” (Comins, 2001, p.35). Comins (2001) asks the readers to imagine being on the Moon while confronting a belief that the Moon has a dark side that we never see. How well can you picture the scene through this description? During the class in this
study, the instructor gives an elaborate explanation about the differences between phases of the two different models using the donut analogy, which left Betty with confusion.

The new opportunities that learners gain through the partnership with Astronomicon can be very powerful: you can place yourself on the Moon instead of imagining it and witness the difference in shapes without any analogy. As many researchers have suggested for almost two decades, the design of tools should be centered on the things that computers can do better than humans without taking over the main cognitive tasks of learners (Dreyfus & Dreyfus, 1986; Norman, 1993). The exemplified cases in this paper demonstrate scientific modeling and observations that would be impossible without Astronomicon and learning experience actualized through the specific pedagogical approach. With this approach, learner is the center of the activity because each phase of modeling-based inquiry was progressed only with learners’ inputs, decisions, and interactions with Astronomicon. The design of Astronomicon as well as the design of the activities has made their experience possible.

Through this study, however, we have found that the way the activities are carried out by the joint learning system is the most important factors for their successful learning experience. The interrelated fundamental causes of the found problems are addressed by suggesting the enhancement of the designs of the tool and the activities. Edelson et al. (1999) put a great emphasis on the learner activities and support of learners’ inquiry processes in addition to the design of their technology. If the design of the tool was only examined in this study, the problems that learners were having as a joint learning system could not have been found as above.

In his book, *Art as Experience*, Dewey stated, “… there is a difference between the art product (statue, painting or whatever), and the work of art. The first is physical and potential; the latter is active and experienced” (Dewey, 1934/1980) (p. 162). Research on learning with technology can easily overlook “the work” that shows learners active and experienced processes. Mindy and Sally both received very good report grades for this particular activity, but remained with the original misconception about the Moon phases according to their post-test result. The mystery was in the missing process of pattern recognition that was critical for their activity. If we do not examine the learning designs in action, we are
left with these mysteries of incompatible data. Our research and development agenda continues pursuing
the rigorous approaches to examine the process as well as the product of the designs of learning systems
in order to understand how they address learning problems and create new opportunities (Kozma, 2000b).

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### Table 2.1

**The expertise structure of Astronomicon**

<table>
<thead>
<tr>
<th>Software: Astronomicon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge:</strong></td>
</tr>
<tr>
<td>Knowledge embodied in the software</td>
</tr>
<tr>
<td>Modeling input interface (providing information about necessary parameters for modeling)</td>
</tr>
<tr>
<td>Relationships among different parameters (e.g., mass, diameter, rotation rate, tilt, radius, orbital period)</td>
</tr>
<tr>
<td>Levels of system complexity (physics-based relationships vs. geometric relationships among bodies)</td>
</tr>
<tr>
<td>Three-dimensional configuration of the space (distance, direction, scale, proportions)</td>
</tr>
<tr>
<td>Relationships among time, space, planetary motions, and light</td>
</tr>
<tr>
<td><strong>Functions:</strong></td>
</tr>
<tr>
<td>Software performing functions</td>
</tr>
<tr>
<td>- to create models: stars, planets, and their relationships</td>
</tr>
<tr>
<td>- to change the perspectives: locations and movements in space</td>
</tr>
<tr>
<td>- to control times: run, accelerate and decelerate, reverse, reset, pause, stop, jump</td>
</tr>
<tr>
<td><strong>Representations:</strong></td>
</tr>
<tr>
<td>Software processed representations</td>
</tr>
<tr>
<td>- Stars and planets</td>
</tr>
<tr>
<td>- Textures</td>
</tr>
<tr>
<td>- Background constellations</td>
</tr>
<tr>
<td>- Light effects (shadows, phases)</td>
</tr>
<tr>
<td>- Planetary motions</td>
</tr>
<tr>
<td>- Scales</td>
</tr>
<tr>
<td>Waypoints:</td>
</tr>
<tr>
<td>- Modeled reality from specific perspectives</td>
</tr>
<tr>
<td>Abstract visualizations:</td>
</tr>
<tr>
<td>- Representations of modeled relationships: orbits, locations, and lights</td>
</tr>
<tr>
<td>Symbols:</td>
</tr>
<tr>
<td>- Body statistics (distance readouts)</td>
</tr>
<tr>
<td>- Timer (day counts)</td>
</tr>
</tbody>
</table>
Table 2.2
Conditions for the inquiry activity, “What causes lunar phases?”

<table>
<thead>
<tr>
<th>Knowledge: Theory to prove or disprove; Required information and knowledge</th>
<th>a. Shadow theory</th>
<th>b. Position theory</th>
<th>c. Dark-side theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases of the moon are caused by a shadow from the earth; Epicycle (concept); Orbital period vs. phase period; Radius</td>
<td>Lunar phases are caused by the changing position of the Moon with respect to the Sun; Actual values</td>
<td>Lunar phases are caused by its own light changing; Orbital period; Rotation rate</td>
<td></td>
</tr>
</tbody>
</table>

| Functions: Functions for modeling and observations | Modeling and epicycle; Overhead view; Earth to Moon waypoint | Software basic modeling; Earth to Moon waypoint | Modeling with Moon texture; Earth to Moon waypoint |

| Representations: Expected representations to be used | Shadow casting; The Moon phases looking from the Earth | Basic light from the star; The Moon phases looking from the Earth | Higher Ambient light setting; The Moon phases looking from the Earth |
### Table 2.3
The distributed structure of the joint learning system using Astronomicon within modeling-based inquiry (MBI) pedagogy

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge</strong></td>
<td><strong>Intended knowledge usage:</strong></td>
<td><strong>Background or constructed knowledge:</strong></td>
</tr>
<tr>
<td></td>
<td>- Questions/theories</td>
<td>- Prior knowledge and misconceptions</td>
</tr>
<tr>
<td></td>
<td>- Concepts</td>
<td>- Collected information from textbook, website, instructor, existing model</td>
</tr>
<tr>
<td></td>
<td>- Required information</td>
<td>Astronomical concepts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- About tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- How to model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- How to observe</td>
</tr>
<tr>
<td><strong>Functions</strong></td>
<td><strong>Guidance on inquiry process:</strong></td>
<td><strong>Executive functions and higher-order thinking:</strong></td>
</tr>
<tr>
<td></td>
<td>- Modeling</td>
<td>MBI-2: Examination of a theory</td>
</tr>
<tr>
<td></td>
<td>- Observation</td>
<td>MBI-3: Modeling and validating</td>
</tr>
<tr>
<td></td>
<td>- Collection</td>
<td>MBI-4: Making observations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Deciding on what to do, what to input, what features to use</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Choosing perspectives</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Recognizing patterns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Matching the observations with their knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBI-5: Making claims and developing arguments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBI-6: Collecting evidence</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Deciding what pictures and numeral values to collect</td>
</tr>
<tr>
<td><strong>Representations</strong></td>
<td><strong>Provided materials:</strong></td>
<td><strong>Learner explored materials or produced artifacts:</strong></td>
</tr>
<tr>
<td></td>
<td>- Textbook</td>
<td>- Websites / datasheets</td>
</tr>
<tr>
<td></td>
<td>- Exercise sheet</td>
<td>- Notes (drawings, data records, observation records, etc.)</td>
</tr>
<tr>
<td></td>
<td>- Websites</td>
<td>- Images from viewpoints</td>
</tr>
<tr>
<td></td>
<td>- Notes on the board</td>
<td>- Reports</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.4  
**Building the model with an epicycle of the Moon**

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Epicycles</td>
<td>(1, 4) Refer to the instructor’s drawing</td>
<td>(2) Modeling input interface</td>
</tr>
<tr>
<td>(4.2) The point orbital period should be 365 to stay on the opposite side</td>
<td>(3) Proper values (diameter, periods, and radius)</td>
<td>(4) Geometric relationship between two objects</td>
</tr>
<tr>
<td></td>
<td>(4) Double the radius for diameter</td>
<td>(18) Relationships among time, space, planetary motions, and light</td>
</tr>
<tr>
<td></td>
<td>(4) Assign a parent object for a planet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4.2) Use the Moon’s radius for the point</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(21) Radius changes the size of an orbit</td>
<td></td>
</tr>
<tr>
<td>Functions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2-4) Start from scratch</td>
<td>(1) Review theory and how to build the model</td>
<td>(5, 22) Apply geometric relationship among objects to the model</td>
</tr>
<tr>
<td>(4.1-4.3) Circular orbits</td>
<td>(4.1) Create Sun and Earth (Sun as parent)</td>
<td>(6) Calculate distance between the selected object and the viewpoint</td>
</tr>
<tr>
<td>(4.2) The point M around the Earth</td>
<td>(4.2) Create point M, Earth as parent</td>
<td>(7) Track objects (blue tracker and blue arrow for locating bodies)</td>
</tr>
<tr>
<td>(4.3) The Moon around the point</td>
<td>(4.3) Create the Moon, the point as its parent</td>
<td></td>
</tr>
<tr>
<td>(6, 13) Objects should be in line</td>
<td>(9) Select and view created objects to check</td>
<td>(10, 14) Locate the viewpoint to specific places</td>
</tr>
<tr>
<td>(20, 21) Need to figure out the radius of the Moon orbit</td>
<td>(13) Judge the alignments among objects</td>
<td>(12, 16) Zoom in and out</td>
</tr>
<tr>
<td>(20-25) The orbit of the Moon should be slightly outside of the shadow</td>
<td>(14) Switch the view</td>
<td>(18) Operate the created model</td>
</tr>
<tr>
<td></td>
<td>(17) Run the model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(20) Recognize that time is too long out of the shadow and too short in the shadow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(21) Modify the radius of the Moon shorter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(23) Repetition of the process 17 through 22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(24) Last iteration 17 through 19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(25) Confirm that the Moon comes out of the shadow and goes in right away</td>
<td></td>
</tr>
<tr>
<td>Representations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Exercise sheet</td>
<td>(1) Notes taken during instructor talk</td>
<td>(4) Sun-Earth-Point M-Moon system</td>
</tr>
<tr>
<td>(3) Website, textbook</td>
<td>(24, 25) Notes (observation records)</td>
<td>(8) Front view with blue tracker displaying object’s name and distance from the viewpoint</td>
</tr>
<tr>
<td>(4) Epicycle drawn on the board</td>
<td></td>
<td>(11, 15) Waypoint: overhead view of the point M or looking at the point M from the Earth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(19) The point M always staying behind the Earth, the Moon moving in and out of the Earth shadow</td>
</tr>
</tbody>
</table>

Note. The number in each parenthesis indicates the typical sequence of operation
### Table 2.5

**The distributed structure of the system of naïve scientism**

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goals of the question</td>
<td>Relevant knowledge</td>
<td>Non-existent relationship</td>
</tr>
<tr>
<td>(B-2: Overall goal is to look at the phases)</td>
<td>(A-8: 29.5 days for the Moon to go through all the phases)</td>
<td>(A-3: Circular orbits, geometric relationship)</td>
</tr>
<tr>
<td>(A-6; B-7: Proof of why or why not it is the one gives real phases)</td>
<td>Interpretation of goals and expectations</td>
<td>Non-existent case</td>
</tr>
<tr>
<td></td>
<td>(B-4: Phases should look different)</td>
<td>(B-1: Moon texture with the completely dark half)</td>
</tr>
<tr>
<td></td>
<td>Making claims for seeming evidences</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(A-9: You should see one set of phases in 29 days)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-7: The half moon never looks like a straight line)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-7: The half moon line by the Earth shadow is straighter)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-7: Gibbous phases should be concave in, not concave out)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-existent relationship</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(A-3: Circular orbits, geometric relationship)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-existent case</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-1: Moon texture with the completely dark half)</td>
<td></td>
</tr>
<tr>
<td><strong>Functions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hints for modeling</td>
<td>Missing the hint</td>
<td>Operating with complexity</td>
</tr>
<tr>
<td>(A-1: Need to figure out the Moon orbital period)</td>
<td>(A-2: Put in the orbital period, 27 days or any number without figuring it out)</td>
<td>(A-4: Accounting for all the input variables)</td>
</tr>
<tr>
<td></td>
<td>Recognizing patterns of motion, light and time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(A-7: 29 or 1 day(s) to move in and out of the shadow twice)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparing the patterns with their memory or common sense</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-6: Unnatural look of phases with clearer lines)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(B-6: A concave-out gibbous phase not looking right)</td>
<td></td>
</tr>
<tr>
<td><strong>Representations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials focused on modeling</td>
<td>Selective attention to the instructor guidance</td>
<td>Broken realism</td>
</tr>
<tr>
<td>(A &amp; B: Exercise sheet, Website, textbook, Epicycle drawn on the board)</td>
<td>(B-4: Notes taken during his talk)</td>
<td>(B-5: With the texture that is half dark and half light, it no longer shows the realistic image of the Moon phases)</td>
</tr>
<tr>
<td></td>
<td>Modeled pattern</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(A-5: With the input 27 days, the day count corresponds to the synodic period)</td>
<td></td>
</tr>
</tbody>
</table>

*Note. The number in each parenthesis indicates the typical sequence of operation*
### Table 2.6

*The second observation of the shadow theory model by Betty and Allen*

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Overall goal is to look at the phases</td>
<td>(2) Phases in-between half and full or new phases should look different (3) No need to compare half moon pictures</td>
<td>(7) Relationships among time, space, planetary motions, and light</td>
</tr>
<tr>
<td><strong>Functions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Look at the differences in-between half and full or new phases</td>
<td>(4) Deleting all the half moon pictures (6) Running the position theory model (9) Checking the shape of the real crescent moon (10) Stopping at the in-between new and half (11) Opening and running the shadow theory model (14) Recognizing the difference in shapes (15) Stopping at the in-between full and half</td>
<td>(8, 11) Operating the model with relationships</td>
</tr>
<tr>
<td><strong>Representations</strong></td>
<td>(5) Note taken from the first observation</td>
<td>(5, 12) Waypoint: from the Earth to the Moon (8) The Moon going through the phases by the Sun light and its respective locations from the Earth (13) The Moon moving in and out of the Earth’s Shadow</td>
</tr>
<tr>
<td>Activity/Instructor</td>
<td>Learner(s)</td>
<td>Tool</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------</td>
<td>------</td>
</tr>
<tr>
<td>Knowledge</td>
<td>(5) Overall goal is to look at the phases</td>
<td>(1) 4 or 5 times of the moon diameter</td>
</tr>
<tr>
<td></td>
<td>(2) Change the point M diameter to 4 or 5 times of the moon diameter</td>
<td>(7) Relationships among time, space, planetary motions, and light</td>
</tr>
<tr>
<td>Functions</td>
<td>(1) Moon radius: 4 or 5 times of the moon diameter</td>
<td>(3) Changing the view</td>
</tr>
<tr>
<td></td>
<td>(5) Look at the Moon from the Earth after building</td>
<td>(4) Putting in 14500 days for the diameter of the point M</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6) Running the model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10) Observing where the shadow goes with the enlarged point M</td>
</tr>
<tr>
<td>Representations</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.1 Classroom setting
Figure 2.2 Astronomicon (overhead view of the Earth)
Figure 2.3 Astronomicon modeling interface
Figure 2.4 Modeling and visualization in Astronomicon
Figure 2.5 Epicycle of the Moon
Note. The size of objects and the distance between them are modified for the illustration
Figure 2.6 Making an epicycle in Astronomicon

Note. The size of objects and the distance between them are modified for the illustration.
Figure 2.7 The Earth to Moon waypoint, Moon moving into the Earth’s shadow (left) and Moon in front of the point M in the shadow (right): Screen captures from Betty and Allen’s Exercise 4 reports
Figure 2.8 A waning gibbous from the dark-side theory model (left) vs. from the position theory model (right, the real phase): Reproduced screen captures
Figure 2.9 Tracing the Earth’s shadow with the big point M: A screen capture from Alice and Marcy’s Exercise 4 reports
CHAPTER 3

THE EVOLUTION OF THE INTELLECTUAL PARTNERSHIP WITH A COGNITIVE TOOL
IN INQUIRY-BASED ASTRONOMY LABORATORY:
ICEBREAKING, GETTING ALONG, AND BONDING

3 Kim, B. To be submitted to The Journal of the Learning Sciences
Abstract

This paper describes a study focused on the longitudinal application of a cognitive tool by observing one group of learners’ interaction with it over an entire semester. 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. I assumed that modeling-based inquiry and the use of the Astronomicon program would result in students acquiring practices that resemble those of scientists.
Throughout the history of education, there have been two primary sources for learning in school. Students have learned from the teacher and from the book, but being solely responsible for their learning outcomes. Realizing that this school education was least effective when learners were not interested in the topics, researchers and educators turned their attention to the ways in which people learn actively outside of school settings. People do not just learn from a source of knowledge, but construct meanings through their activities, guided by their own interests or by situational demands (Duffy & Cunningham, 1996).

Inquiry-based pedagogies focus on the question of how people solve problems and create explanations about the world (Greeno, Collins, & Resnick, 1996). Scientists construct simplified models of the world and use them as their inquiry tools (Penner, 2001). Advances in technology have introduced computerized modeling and visualizations to scientific inquiry practices (White & Frederiksen, 2000). Modeling and visualization tools then 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. Research on such inquiry approaches discusses tool usages and knowledge gains of learners (Spitulnik, Krajcik, & Soloway, 1999). 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 and interactions
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. I 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: 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, p.693). 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 technology with unique capabilities
that complement learners’ cognition (Kozma, 1991). The conceptual framework of this research started
with the ideas of distributed cognition, and was elaborated with the theory of expertise.

An Alternative View on Cognitive Tools

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 have 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 it 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 one (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 the 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 the performance of experts and their development of expertise. In developing expertise, especially in early stages, one should develop a basic structure of expertise in the domain, which involves better use 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; Winn & Snyder, 1996). As a joint learning system, learners’ knowledge, the tool, and the current setting (activity and environment) is 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 more based 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 their repeated performances on problem-solving tasks, which enable them to use their cognitive resources to the novel aspects of the current problem (Schneider, 1993; Winn & Snyder, 1996). With gained expertise, learners would no longer need to make cognitive efforts to understand the tool itself. The cognitive functions of the learners and the tool should become well-coordinated through the development of expertise.

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 decision-makings and actions (Ericsson, 1996; Glaser, 1996; Winn & Snyder, 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 conceptual framework outlined above. First, the cognition is distributed within the joint learning system during students’ learning (Salomon, 1993). Second, the way a joint learning system develops through students’ extended learning experience is 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). There are three main questions for this study:
1. How does the joint learning system (two learners with Astronomicon) develop intellectual partnership?

2. How does it gain expertise over an entire semester in scientific inquiry using the tool?

3. What supports or hinders the development of a joint learning system?

The process of developing expertise with a cognitive tool is extremely complex to study, as it needs to account for relationship with technology in addition to the human interactions (Kozma, 2000b). This research adopted a video-based approach to capture the development processes of learners working with a cognitive tool for a semester-long laboratory course.

Research Set-up

In this particular learning situation, learners develop their scientific knowledge and inquiry skills using an innovative cognitive tool within an inquiry-based pedagogical approach. As an undergraduate astronomy reform effort at the University of Georgia, Virtual Reality Modeling Project (VRMP) implemented a unique learning approach to an introductory astronomy lab. This course is characterized by a modeling-based inquiry (MBI) pedagogical approach and a three dimensional (3D) model construction tool called Astronomicon. To enhance students’ understanding of astronomy, it covers basic topics, such as orbits, time, phases, eclipses, and seasons.

Astronomicon

Astronomicon: Celestial Construction Tool Kit is a computer modeling tool for astronomy learning, especially planetary motion and light. Learners build and simulate their own models of solar systems within a 3D environment (see Figure 3.1). The models that learners create using Astronomicon can be used not only as surrogates of our solar system, but also as experimentations of non-existing systems. These 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).

- Insert Figure 3.1 about here -
The important knowledge of Astronomicon is the underlying physics for relationships among relevant measures (e.g., masses and sizes of objects, distance between objects, and parent-child relationships). Its functions are the executions of various operations controlled by learners, such as running the models, switching among perspectives, and changing the running speeds. Its representations are chiefly isomorphic, keeping the ratio of physical values such as size and distance, and can be complemented with other abstract representations (e.g., orbital disks). Figure 3.1 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
- The blue box indicates that the Moon is selected
- The window on the bottom right is showing the properties of the moon
- The window on the top left is to control the model to run, accelerate, decelerate, pause, stop, and jump forward and backward (e.g., jumping to a year ago or a year after)

**Modeling-Based Inquiry and Astronomy Lab**

Modeling-based inquiry (MBI) (Hay, 2000) is a specific pedagogical approach that focuses on computer modeling to investigate and learn about phenomena. Modeling refers to creating a simpler representation of a complex system or phenomenon to understand the underlying relationships among different components of the system or factors causing the phenomenon (Penner, 2001). Modeling and visualization practices promote creating explicit theories of models and of inquiry processes, which is comparable to the practices of scientists (White & Frederiksen, 2000). The process of MBI includes: 1) begin with an inquiry question, 2) plan the model and collect data, 3) create the model of the phenomenon, 4) validate the model and revise if necessary, 5) use the model as a source of data to address the original question, 6) visualize data to explore relationships, 7) develop a warranted conclusion, and 8) present conclusions to colleagues. Through MBI, students engage in the model-building practices to try out their hypotheses, methods, and strategies using the similar processes of experts.

The inquiry activities in this lab directly addressed common misconceptions of astronomical concepts. Learners built models to test theories with proper and alternative conceptions to explain a
phenomenon (such as phases). To do that, they had to find the fundamental concepts, steps, and information to work with. Learners worked on 6 two-week-long exercises as listed below:

- Lab Introduction
- Software Introduction
- Exercise 1: Basic Solar System Observation
- Exercise 2: Timekeeping / Day and Night
- Exercise 3: Orbital Motion
- Exercise 4: The Moon and Phases
- Exercise 5: Eclipses
- Exercise 6: Seasons
- Wrap-up / Final Presentation

Lab and software introductions involved introducing this different way of approaching astronomical problems and the 3D modeling space.

Learners in this lab were undergraduate students, mostly taking this lab along with an introductory lecture in order to fulfill their science requirements. Only a few are science majors. Most of them were not aware of this novel lab format before coming to the class. They worked collaboratively in pairs throughout the semester with an individual laptop computer having an internet connection. 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 throughout the Fall 2003 semester as a case to focus on the transitions and changes of their learning. The in-class observation was focused on the overall process of the lab, and the detailed interaction was analyzed using the video data.

_A Systemic Look with Video-Based Research_

Pea (1993) suggested two ways of examining intellectual partnerships: analytic (the specific contributions made by person(s) and technology to the performance) and systemic (the aggregate performance of the person-computer system). In this particular setting, learners came into the setting where the curriculum and the software above were uniquely combined. They started developing the joint
system, and their roles and relationships evolved with increasing complexity of activities and learners’ knowledge base and strategies.

In order to examine how learners gain expertise in tool use and scientific inquiry and develop intellectual partnership as a joint learning system, we took the systemic approach of examining the aggregate performance of the joint learning system. The critical incidences that especially helped their development were investigated within the expertise framework with the three primary elements of expertise (knowledge, functions, and representations). The pattern of development was examined regarding how knowledge was used and constructed, how different functions were performed, and how representations were used and understood.

This study 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 that of 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.

The in-class observation accompanied throughout the semester for proper contextualization during analysis (Jordan & Henderson, 1995). In addition, other sources, such as learners’ lab notes and written reports, helped provide a more complete understanding of their learning. The results of pre and post tests indicated overall improvements in basic astronomy knowledge. Surveys and interviews were conducted to understand learners’ backgrounds, interests, and comfort levels. Occasional conversations with the instructor helped the researcher understand learner activities and underlying concepts, as well as his expectations and concerns about learners.

Betty and Allen: The Prehistory

The causes and consequences of current interactions of a joint learning system cannot be completely explained without a deep understanding of each participant’s history. We need to understand
what the learners bring into the relationships and their potential contributions to the distributed structures for learning activities. The following accounts are based on the results of the pretest and the survey conducted before they were introduced to Astronomicon and lab activities. As summarized in Table 3.1, the results of the pretest showed some misconceptions and lack of domain knowledge, which would consequently influence the cognitive activities of the joint learning system.

- Insert Table 3.1 about here -

Betty was a sophomore in a social science major, taking this lab and the lecture as her first college-level astronomy course, in order to fulfill some requirements. She was somewhat interested in astronomy and had assumed that they would be looking at planets and stars. She self-assessed her math ability as generally poor and her science ability about an average. She previously had done group work and a statistics computer lab. She expressed her confidence in the pretest, in which she correctly answered about 38 percent of the relevant questions (the class average with about 44 percent). Regarding the scale of solar system, she underestimated the relative size and distance between objects. She answered that the revolution of the earth around the sun caused day and night on earth, showing a lack of knowledge on the relationships among objects. She had the two common misconceptions that the lunar phases are caused by the Earth’s shadow and 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. Betty thought that an eclipse can happen on any lunar phase (it should be in full phase).

Allen was a senior in a social science major who is retaking two courses (lecture and lab) after several years. He has read magazines and books about astronomy and believed that the lab work would further his understanding of the universe. He assessed his performances in math and science as generally good and felt confident enough to do the lab work. He had some experiences in group work and never had a lab course using computers. Allen was uncertain about how well he did on the pretest (53 percent correct), which showed some misconceptions. He also underestimated the scale of the solar system and showed his lack of understanding on the relations between rotations and revolutions of planets. Allen did not have the common lunar phase misconception, but thought that the lunar phases would be different
when seen from the different places on Earth. For the questions related to seasons, his answers showed that he was constantly relating 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).

The Evolving Expertise and Partnership of the Joint Learning System

Learners in this class were involved in both the role negotiation with their partners and dealing with initial conflicts with the tool. On the first day of the class, learners met their potential partners including their lab partner and Astronomicon as a “partner in cognition” (Salomon, Perkins, & Globerson, 1991). Learners began developing their partnerships as well as their knowledge and inquiry skills when they started working in pairs the following week.

Overview of the Semester

Learners made their first contact with Astronomicon and started some cognitive connection with it in their image of and knowledge about the solar system during the second week. The first two exercises (basic observations and time) were focused on basic model building and observation techniques, including viewing from various points in the system and keeping track of time in regard to planetary light and motions. Through these exercises, learners became familiar with basic features of Astronomicon and essential characteristics that made up each solar system object because they were engaged in the construction of multiple objects, repetitive observation practices, and testing of various variables such as mass and distance. During these four weeks (two weeks for each exercise), learners came to have more constant roles as to who drove Astronomicon, who asked more questions to the instructor, and who looked up the web resources in each group.

For the subsequent two exercises (Orbits and Phases), learners worked mainly on making models to test and compare theories to answer inquiry questions, usually one question each week. Learners were becoming more familiar with the way they worked together as partners in this lab. Beyond basic model building of inputting appropriate information in correct places, learners were engaged in quite complicated modeling of common astronomical misconceptions. The instructor had to provide long
lectures regarding how to build those models at the beginning of each class. Learners who overcame the challenges with these two exercises grew much stronger as joint learning systems.

The last two exercises, on Eclipses and Seasons, did not involve any new modeling techniques, and in fact learners only needed to build the basic Sun-Earth-Moon system most of the time. These exercises, however, assumed more independent inquiry practices of learners, requiring them to plan their own models, to reason through the underlying causes and outcomes of phenomena, and to alter certain phenomena by changing key factors. Their tasks for each week included not only answering an inquiry question but also exploring the effects of parameters on systems. The instructor thus proceeded each day mainly with some minor hints on modeling and observations, and assigning questions to different groups.

*Negotiating Roles between Betty and Allen*

As learners were walking into the classroom on the second day, they randomly chose where to sit, which became almost their permanent choice of seats and lab partners. On this day, Betty and Allen become partners. Betty and Allen went through the process of finding their roles as partners until after the mid-point of the semester. At the same time, they developed different relationships with Astronomicon because of their roles.

*Icebreaking and Initial Role Defining*

The interactions and conversations between Betty and Allen showed some of the characteristics that affected their roles. Betty initiated conversations much more than Allen did on the first day they worked as partners. Allen tried to figure things out himself, whereas Betty made constant comments about her model and asked questions when she ran into problems. When Betty raised her hand to get the instructor’s attention for a problem, Allen tried to give her a solution.

When they were encouraged to work together for eccentricity practice, Betty tried to make the decision of whether to use her computer or Allen’s. Allen, on the other hand, just started working on making a new model for the task [1].

1. Betty: [watching Allen making the Sun] Alright, you want to do it or you want me to do it?
2. Allen: Um... what are we doing, the 4 planets?
3. Betty: Yeah, on the sun, different eccentricity, the same everything else.

4. Allen: Okay. [finishing making the Sun]

5. Betty: Did you make a new one or do you have all the planets you made?

6. Allen: Oh, I started a new one. [adding a new planet, elliptical orbit around the Sun]

7. Betty: Eccentricity is what we need to change... okay, it can’t be 1, he said.

8. Allen: Right it can’t be 1 or 0... So I guess start with .01?

9. Betty: Sounds good to me.

Allen changed the focus of their conversation from which computer to use to what their task is and continues on modeling [1-4]. Without any agreement, the control of Astronomicon goes to Allen on this day. Betty takes on the role of providing information for their task [3, 7] and making sure that they are doing it correctly [5].

The Significance of Betty’s Role

On the first day of exercise 1, Betty was absent due to illness. Allen worked by himself and was engaged in building models and exploring waypoints (shortcuts to the perspectives). Betty’s absence significantly deteriorated her performance the following week and weakened the group’s intellectual partnership as a joint learning system. Both Betty and Allen were confused and could not connect and work well with Astronomicon. Betty had forgotten some details she learned about Astronomicon during the previous two weeks. Betty, therefore, followed the lead of Allen without discussing who would do the modeling. Allen’s role of modeling was continued but not yet formally agreed upon.

Betty’s role, however, already appeared to be very critical for the performance of this joint learning system. Allen, who liked to explore with Astronomicon, spent the lab time less focused on the details of the tasks. Many hints and detailed information regarding this exercise were given by the instructor on the first day, but Allen did not pay as much attention as Betty would have. Betty, even with her previous absence, attended to the details and maintained the focus of their task throughout their modeling, observations, and data collections. For example, when Allen was about to attach a waypoint to start observing a model, Betty pointed out that they needed to make the Moon first. When Allen was
carried away with whatever view he was interested in, she reminded him of the instructor’s advice on using the same waypoints they had used for other model.

Role Transition Attempt

Beginning exercise 2, Betty decided that she wanted to make her own model and collect separate data so that she could understand better what was going on. Their first task was to define and time the length of a day according to their definition. While Betty was talking through and taking note of their definitions, Allen started building the model. To catch up with his model of the Sun-Earth-Moon system and observing a day (with ‘sunrise to sunrise’ as their definition), Betty copied input values from Allen’s model and imitated Allen’s waypoint. While timing the length of a day, she became frustrated by getting the timing results of 0.5 day instead of 0.99. Without clearly delineating their roles and sharing of models, Betty was not involved in Allen’s decisions on modeling and observations. As a result, Betty’s model and waypoint were created without her understanding of underlying relationships. After recollecting and recalculating the numbers for a day several times, thinking that she was doing exactly what Allen was doing, she finally said, “I am just going to go with yours,” and turned toward Allen.

Instead of transitioning to model-building, Betty further elaborated her role of keeping up with their progress. Betty later realized that she was timing ‘sunrise to sunset’ instead of ‘sunrise to sunrise’ while observing together with Allen, but she continued working with him. Betty started taking notes for all of the observations and data, which largely helped their report writing. On the outset of timing a month, Allen recklessly used the same waypoint for timing a day. Betty said, “Our definition of a month is the time it takes to go through the full cycle of lunar phases.” Allen then made a waypoint looking at the Moon from the Earth in order to observe the lunar phases.

Affirmation of the Roles

The roles of Betty and Allen were already apparent in the previous exercises, but they were never agreed upon. Beginning a new exercise (3), Betty again paused to work with Allen’s model. Betty tried to decide whether she should make her own system or not [10-14]. Betty asked Allen and the instructor how other people were doing their modeling and what they thought of working together with one system [15-.
19]. The instructor told her that it would be their choice, and Betty turned that question to Allen [20-22].

10. Betty: [closing Astronomicon] I am not going to make a new system because you already have a saved system on your computer.

11. Allen: I was actually going to make another one.

12. Betty: Well, then I’ll go ahead and make one too then. [reopening Astronomicon]

13. Betty: [starting to make the Sun with data from the Web and then pausing] That would never work [exiting Astronomicon]. I am just going to use yours… [turning toward Allen]


15. Betty: I mean, is everyone else making their own system? [both looking around the classroom]


17. Betty: [looking at Allen] Yeah?


19. Betty: [to instructor] I have a question. Should we make separate systems? Is everybody making their own system?

20. Instructor: [smiling] Well, some do and some don’t. I mean, you can make your own system or work together and share. It is your choice.

21. Betty: Okay. [to Allen] Do you want me to make my own?

22. Allen: No… I mean, we can make this system and save it with different names so that we don’t have to put in numbers every time.

After this point of starting exercise 3, Betty and Allen found their comfort zone as working as a team. Unlike Allen, Betty had not become comfortable with driving Astronomicon and no longer tried to make her own system. Allen, from here forward, became even more dependent on Betty’s various roles, including providing information, making sure they have all the necessary data, and taking notes about their observations. For his lab report, Allen relied on the file names that he gave to the collected pictures up to this point. At the end of the exercise 4 lab, he asked Betty to share her notes, which became their usual procedure for wrapping up the lab.
Toward a Coherent Knowledge Structure and Strong Methods

The focus of a cognitive tool in inquiry-based learning is not just on gaining scientific knowledge. Knowledge and problem-solving strategies are means for, as well as products of the inquiry process and working with the tool. Novices who are in the stage of becoming familiar with the domain 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. The knowledge is used, understood, and elaborated within their activities. Their weak methods of being dependant upon concrete information develop toward the strong methods of abstract reasoning.

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 is characteristic of novices in most expertise literature (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.

As one of the novice traits, learners maintained their interest on the surface features of Astronomicon and their manipulation of these features. When first practicing model-building, Betty made planets with various available planet textures and gave them interesting names like Blue and Sharpie. When they worked together for the eccentricity exercise with four different Earths, Allen applied multiple kinds of Earth’s textures to the planets (e.g., the textures of the Earth’s topographical image, the satellite image texture with clouds, and textures with different resolutions).

The nature and the purpose of knowledge in a field affect how knowledge is organized and processed for better performances (Anzai, 1991). The relationships among concepts of planetary light and motions can be better understood by visually observing the effect of them. One of the main constructs that determine the planetary motion of the solar system is eccentricity (the extent to which an elliptical orbit
departs from a circular one; it ranges between 0 and 1, 0 being a circle). Eccentricity is the very first concept that learners explored in the class and continuously dealt with for their inquiry throughout the course. 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 with Astronomicon.

**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 4 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* ($e$) was a word without a meaning for the learners, and its input values were numbers without any association with the concept. Earlier in the class, Betty had trouble with her input for eccentricity [23-24]. Allen gave her the right value range ($<1$), but incorrect information that eccentricity 1 meant a circle [25].

23. [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.]

24. Betty: Huh… between 0 and 1… Is my eccentricity wrong? [currently 5]

25. Allen: Yes. Because eccentricity 1 means circular. In order for it to be elliptical you have to make it less than 1.

26. Betty: Could be that? [putting in .00002].

27. Allen: You can try. I don’t see why not. I guess that’s the whole point of the program.

At this point, Betty’s input did not mean more than a random experiment to her and to Allen, even though Allen had a better sense of eccentricity.

Later, when they worked on the 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 pretty close to zero (E1, $\varepsilon=.01$; E2, $\varepsilon=.03$; E3, $\varepsilon=.05$; and E4, $\varepsilon=.07$). All four planets were closely aligned together, almost overlapping with each other [28-33].

28. Allen: I don’t know what that did. I guess we will find out.

29. Betty: I guess maybe it is hiding behind another one, maybe.

30. Allen: Let’s try... [making a new waypoint, E1 to E3]

31. [As he runs the model, E3 moves forward and backward from very close view and other planets are also seen from very close positions.]

32. Allen: What in the world?

33. Betty: I think they are running into each other...

Using orbital disks, they realized that the differences among eccentricities values were not significant enough to make the orbit shapes to have noticeable differences [34-38]. As they changed the values to have bigger differences, they saw the differences in shapes [39-43].

34. Betty: Maybe we should view it with the orbit thing. You know what I am saying?

35. Allen: Oh, Ah, Good! [going to the menu and turning on orbital disks for planets]

36. [As the orbital disk of each planet is turned on, one by one, the shapes of orbits show, which are all close to circles.]

37. Allen: Okay, let’s do this... actually make the eccentricities further apart.

38. Betty: Okay, good call.

39. Allen: ’Cause it can be between 1 and 0, so we got a lot to play with.

40. Betty: And we will be able to see it better.

41. Allen: [modifying E2 ($\varepsilon=.1$)] Now, orbital disk... [turning on its orbital disk] Little bit better?

42. Betty: Yeah. [Allen changing the eccentricities of E3 ($\varepsilon=.3$) and E4 ($\varepsilon=.8$), and turning on orbital disks.] (see, Figure 3.2)

43. Betty: Okay, the closer to zero, the more circular they are.

44. Allen: Yeah, it was zero, not the other way around.

- Insert Figure 3.2 about here -
Here, Betty played a significant role in creating a meaning of eccentricity by suggesting utilizing visual representations of orbits [34-35]. Orbital disks enabled them to see the actual shapes of the orbits, which helped them to understand what the eccentricity values represented [43]. Allen finally realized that the information he provided to Betty about eccentricity was incorrect [44].

Through this process of working with new partners (Allen’s manipulation of Astronomicon, Betty’s suggestion of using orbital disks, and Astronomicon’s production of models and visuals), definitional, numeral, and visual meanings of eccentricity became associated together in their knowledge structure. They became familiar with the most basic level inquiry strategy (trial-error approach) and the use of visual representations (orbital disks) through focused exploration of one variable (eccentricity), comprised their first step toward the development of expertise (its knowledge, functions, and representations).

*Orbits and Eccentricity*

The subsequent four weeks with first two exercises (Basic observations and Time) prepared Betty and Allen with basic modeling and observation skills and system variable knowledge (e.g., mass, distance, rotation rate, and orbital period). They then performed their inquiry with some understanding of underlying relationships among parameters and their relevance to the current observations. For example, building a model for exercise 3 (Orbital motion), Allen did not bother to input exact rotation rate of planets. They had practice observing the solar system from various waypoints and knew that most of the planets would look as small as dots from an overhead view to observe the orbital movements. They instead focused on other values that would affect orbits, such as eccentricity.

In the following example Betty and Allen had just finished making their initial model for the theory that *all planetary orbits are quite elliptical*. By modeling and operating this theory, Betty and Allen elaborated the concept of eccentricity. They first made Mercury ($\varepsilon = .3$), Venus ($\varepsilon = .4$), Earth ($\varepsilon = .5$), the moon ($\varepsilon = .3$), and Pluto ($\varepsilon = .25$) around the Sun, but did not see much difference in orbit shapes among planets. They then changed the eccentricity of the Earth to a bigger value [45-46] and started seeing extreme effects of an eccentric orbit [47-48].
45. Betty: They still look pretty circular.

46. Allen: I am going to actually change them more elliptical [changing Earth’s eccentricity to .9]

47. 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.

48. Betty: [watching the screen] Yeah... crazy.

49. Allen: [Earth moving from the far side of the orbit around the Sun] See how slow it goes...

50. Betty: So where is the Earth now?

51. 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]

52. Allen: [Earth moving much faster closer to the Sun] Shook! [stopping and resetting the model] I guess we need to do some waypoints actually.

53. Betty: Yeah. Well, hang on… Okay, 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.

54. [Allen nods his head and turns on the orbital disks of the Earth and Mercury.] (Figure 3.3)

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 [47, 53]. Another observation was on the effect that the eccentricity had on the planet’s speed of movement [49-52].

- Insert Figure 3.3 about here -

From the above excerpt, we can find some indications for the development of distributed expertise. They elaborated their knowledge structure by associating speed and positional relationships with the concept of eccentricity. They no longer used basic trial-error approaches, but observed with some
expectations of the results [51]. The use of the representations is in support of their arguments, having clear purposes [53]. Allen showed more interest in what happened with the model, whereas Betty was interested in how to use the representations to support their claims.

**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, they did not know what they would get from that change. During the eclipses exercise, however, Betty and Allen made changes to the parameters with certain expectations about the results because they were able to think of the possible effects or no effects on the phenomena without being solely dependent on Astronomicon. 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 excerpt, they were about to think about eccentricity in order to change the frequency of eclipses [58].

55. Allen: If we change... how much the Moon goes around the Earth, it might change…

56. Betty: Okay…Rotation rate? No, that’s rotation around the axis, isn’t it? Oh, could we change the eccentricity to be smaller?

57. Allen: I don’t know what that would do.

58. Betty: No, it wouldn’t ’cause it is already almost circular. Or we could make the eccentricity bigger.

59. Allen: More elliptical?

60. Betty: It would reduce the number of eclipses, wouldn’t it?

61. Allen: Do you want to make it really eccentric? [opening the Moon edit window]

62. Betty: Yeah, like point seven.

63. Allen: [putting in .7 and running the model from the Moon to Earth view] Let’s look and see what happens at 121.
64. [The timer count passes day 121 and they do not see any shadow going by.]

65. Allen: [stopping the model] No eclipse… so do you want to take a picture here when we do not have one?

66. Betty: I don’t know. Let’s wait until we see the first one. It might never happen.

67. 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 [58-63]. They checked the day (about 121 days) when they had the first solar eclipse in the real system [63-65]. They found that a more elliptical orbit would take a lot longer to have the Sun, Moon, and Earth in line. They associated another aspect (eclipses) to their knowledge structure about eccentricity. Figure 3.4 is from the lab reports of Betty and Allen, which shows their use of orbital disks to demonstrate that the Earth and the Moon were in line with the Sun.

- Insert Figure 3.4 about here -

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 of the solar system. They also explored how the change in eccentricity affected seasons on a planet because of the resulting variations on the orbit’s speed and distance.

- Insert Figure 3.5 about here -

Betty and Allen, by this time, were able to abstractly reason through the model’s operation based on their knowledge of underlying principles. In the following excerpts, they collegially brainstormed to model the theory that seasons are influenced by the Earth’s changing speed in its orbit. Allen opened the edit window of the Earth (Figure 3.5) to see different parameters they could change [68-69]. The first thing he considered changing was the eccentricity, with which they had seen the speed variations from previous exercises [69-71].

68. Betty: Alright, how do you change the speed of the orbit?
69. [Allen selects the Earth, opens its edit window, and clicks on the eccentricity box.]

70. Betty: Now how would that change?

71. 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 by it when it’s real close.

    [drawing an orbit with his right index finger]

72. Betty: Right... now that would change it because that would make it go further away from the
    Sun?

    -Insert Figure 3.6 about here -

They changed the eccentricity of the Earth from .02 to .7, attached an orbital path, and started
talking about other factors [73-75] (Figure 3.6).

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

74. Betty: No tilt.

75. Allen: No spinning.

76. 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...

77. Betty: Sun?

78. Allen: Right... so I don’t think that would work.

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

80. Allen: [watching the screen] With that elliptical orbit, I think it will still be the same. (see,
    Figure 3.6)

81. Betty: You mean, seasons?

82. 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].

83. 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 [76-79]. As Betty had the knowledge that the tilt affects the seasons on Earth, she considered it to be the main factor [73]. They finally came to realize that the tilt should no longer matter in a different condition (extremely elliptical orbit) [80-83].

From the above incident, we can infer that the way Betty and Allen were thinking 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. This was not the case for the latter. This kind of abstract reasoning is possible only when learners understand the characteristics of relevant values.

*Perspectives and scientific investigations*

One of the main reasons to learn using a 3D environment is to better understand a phenomenon by having a perceptual experience that we cannot have otherwise. It provides a means for viewing reality from different angles (Pagels, 1988). Astronomicon provides a 3D modeling space where learners can explore the unimaginable scale of scientific phenomena from various perspectives. The capability of traveling through space becomes valuable when learners do understand the perspectives they are taking. Learners should ultimately gain some automaticity in finding their orientation so that they can focus more on understanding the phenomena on task.

Learning to use Astronomicon was an ongoing process until the last day of the class because every new exercise required using it in different ways, and learners discovered its different capabilities as they gained more insights. For Betty and Allen, using waypoints in Astronomicon was one of the important influences for strong or weak cognitive partnerships. One of the known characteristics of novices is their use of surface-level strategies (Alexander, 2003). Their scientific investigations remained unfocused, often accounting for irrelevant measures, especially when they were confused about where
they were in space. As a result, Betty and Allen were randomly collecting good-looking picture data without any rationale behind it. When they finally got to attach their perception to the waypoint, they were able to engage in deeper inquiry. Without understanding what the current view of Astronomicon represents, the created effects of planetary motion and light in the 3D space would not mean anything to the learners.

The Perspective Confusion

On the first day of exercise 1 (Basic observation) when Betty was absent, Allen focused on understanding and exploring Astronomicon by making and switching among various waypoints, some of which were not even necessary for their task. On the second day, Allen started using waypoints he set up previous week, which he had made without attending to the details that the instructor mentioned (uncheck “Stay above the same point on planet” option and make offsets to zero; Figure 3.7). Allen’s waypoints were made to stay on the surface of an object, looking at another. With that waypoint all other objects appeared to move in odd directions, in order to stay at a point and maintain the focus to the target (at the center, staying upright). Starting their observation, Allen attached a waypoint looking from Sun to Earth [84]. Betty and Allen became confused with what was happening and started questioning the model, not the waypoint [85-94].

84. Allen: Okay... look from the Sun [selecting the waypoint, Sun to Earth]
85. [As Allen runs the model, the planets move upward and downward.] (Figure 3.8)
86. Betty: I have no idea what’s going on. What’s that big rolling planet? That’s Jupiter?
87. Allen: I think so... why they go up? …I don’t know... might have to do with the inclination...
88. Betty: [watching the model running as all planets but Earth move up or down from the center] I am kind of confused. Why are they moving up and down?
89. [Both of them tilt their heads to the right, seeing the plane of the planets’ movement turning.]
90. Allen: So am I [checking values of planets in each edit window].
91. [The surface of the Sun begins to show and then occupies entire screen.]
92. Allen: Oh, that’s surface of the Sun. The Earth is going behind, going under us basically.
Betty: Maybe it is because the Sun is rotating, too?

Allen: Oh, yeah, that is very possible.

Betty and Allen questioned the planet’s inclinations and the Sun’s rotation rate instead of waypoints for their problem [87, 93].

- Insert Figure 3.7 and 3.8 about here -

Betty, Allen, and Astronomicon were working together as a team, but what was distributed among them was the total confusion—no effective thinking whatsoever. They were thinking with wrong aspects of Astronomicon (its modeling capability instead of its 3D perspective construction). With the unresolved perspective problem, they spent this day collecting pictures of views that looked good to them (showing as many planets as possible) without much intellectual growth.

Understanding Waypoints

Betty and Allen continuously had problems with waypoints for the next 4 weeks until the beginning of exercise 4. The capability of Astronomicon to set up the view anywhere on a planet (‘Stay above same point’ option) or at any coordinate position from the center of a planet (X/Y/Z offsets), in their case, was not a useful feature, but a huge trouble that hindered their engagement in inquiry. The partnership of the joint system, especially during the second day of exercise 1, thus went through weak and strong phases, depending on whether their current waypoint was at a relatively sound position to do their observation.

An opportunity came during this class to address the waypoint problems. Betty and Allen asked a question of the instructor for their modeling problem for lunar phases. The instructor first suggested making an appropriate waypoint to test the model [95], which led to explaining the waypoint choices.

Instructor: Okay, let’s make a waypoint from the Earth looking at the point M.

Allen: [opening and looking at the list of waypoints] We have… Earth looking at the Moon works? Or you want the M?

Instructor: Yeah, point M would work better.
Allen: [clicking on ‘Add Waypoint’] I hate the fact that we are still working on the waypoint...

[with the waypoint dialogue window open, naming the waypoint ‘earth to point m’ and selecting the Earth] we want to stay above same point?

Instructor: No.

Allen: No? Okay. [leaving the option to stay above same point unchecked]

Instructor: Very rarely you need to stay above same point. And make all your offsets to zero.

Allen: Oh, okay. [changing the offset values to 0]

Instructor: That’s pretty much the standard that I would use.

Even though his waypoint help was not recognized as significant, their perspective problems were resolved by making the waypoint with the instructor [98-103]. When they habitually selected the option of staying above same point, they did not seem to be conscious of what it meant. This short moment of turning their attention to those two aspects of waypoints, however, made them aware of what their choices would entail. From this point on, the joint learning system became much more capable of proceeding with their inquiry. Astronomicon came to truly contribute its unique capabilities to their learning because Betty and Allen now understood the created representations viewed from the waypoints.

**Quality of Investigation**

The clearer understanding about waypoint had a significant role in the dramatic change in their work with waypoints. After the instructor helped them with the waypoint, Betty and Allen answered another question: “Do lunar phases depend on where on the Earth you are?”, which in fact required them to stay above a point on Earth at all times for their observations. When they carefully looked at the boxes on the waypoint window, they started to see the ways to go to different places on Earth [104-105]. During this activity, Betty played an important role in employing the capacity of this waypoint feature and in making their observations more precise by finding a way to place them at a specific city on Earth [106].

Betty: I don’t know how we tell if we are different parts of the earth or not.

Allen: [new waypoint: ‘earth to moon 1’; checking on the staying above same point surface option; and having 0s on the boxes as default] So, with zero latitude and zero longitude,
meaning, we are on the equator now… Okay, let’s do this. [typing in 15, 12, 11, N; 15, 12, 11, W in the boxes] Okay, let’s write down these numbers. (Figure 3.7)

106. Betty: [writing down numbers] Wish I knew which point on Earth we are at. We are probably like... oh, let’s find... [turning to her computer and finding a webpage providing longitude and latitude values of world cities.]

107. Betty: [with a long list of cities and their values on a webpage] Okay let’s do this...

108. Allen: [looking at Betty’s screen] How did you get to go there?

109. Betty: I just typed longitude and latitude. [scrolling up and down on the page] Okay,...do you want to go to Mexico, the only place I recognize…?


111. Betty: Okay, Tijuana, Mexico… 32, 32 north, and 117, 01 west.

When Allen started putting in some random numbers to be on a specific place on Earth, Betty wanted to be more specific on where they were on Earth [105-106]. Betty found a webpage that had information about the locations (longitude and latitude values) of world cities, and they could observe the Moon from specific cities on Earth [106-111]. This indicates their decision-making functions that moved beyond what was required in the exercise and their improvement on the use of representations that had more precisions and were more meaningful.

Thriving with Waypoints

When Betty and Allen were confused with their perspectives, they could only focus on figuring out what was happening at that moment. By becoming familiar with the various perspectives and waypoint properties, they easily found required information and readily understood where they were in space. This left some cognitive capacity for them to engage better in higher-level thinking and to systematically use Astronomicon to observe and represent phenomena. Some advanced inquiry functions, such as making predictions, are important for cognitive development (Ericsson, 1996). Whether confirming or contradicting, learners would better understand the concept by comparing the result with their expectations, developing a more cohesive knowledge structure.
Waypoint again turned out to be an important portion of their observation for the last exercise, Seasons. In order to observe the temperature variations of a place on Earth, they had to make a waypoint that was looking at a place on a planet (as oppose to looking from a point on a planet) for the first time (Figure 3.9). They make the ‘athens’ waypoint to observe the luminosity variations around a certain area on Earth over a year. Allen started making a waypoint based on the given information (latitude, 34 North) and realized that they would not be observing the right location [112-113].

112. [Allen adds a waypoint: naming it ‘athens,’ attaching it to Earth, checking ‘Staying above same point on planet’, and inputting Latitude 34, N and Altitude 100000 meters.]

113. Allen: We are not over Athens, wherever that zero longitude... can you find the website you were on?

114. Betty: I am not sure. They didn’t have Athens on there. [opening a search site on the Internet]

115. [Allen clicks OK button, and some part of the Earth is shown on the screen.]

116. Betty: [a website with detailed longitude and latitude values for Athens] Okay, here it is.

117. Allen: Oh, cool. [opening the waypoint window]

118. Betty: 33, 57, 36 north, 83, 22, 40.8 west [Allen typing in the values]

119. [Earth is not at the center of the screen. Allen goes back to the waypoint window and changes it to look at Earth. Earth looks very close from the view.]

120. Allen: Too close…add a couple more zeros? [changing the altitude to 100000000]

Without any guidance from the instructor, Betty and Allen were able to find their way to get to the position they wanted [113-118] and to look toward the right direction [119]. This excerpt implies that Betty and Allen became able to make, understand, and switch among different waypoints as a team with a clear understanding of their inputs and the resulting view. Their insights on these perspectives maintained the quality of their observations.

Up to the point where they made their first observation from a waypoint, Allen mostly drove their work. He planned for their next step and predicted what they would see from it. Betty’s main role
involved monitoring the process and providing information. Once they were engaged in finding patterns and making decisions on how else they should observe the model and which data to collect, Betty and Allen worked very dependent on each other and, of course, on Astronomicon for their investigations.

The next example shows how Allen’s driving of Astronomicon, Betty’s insights on viewpoints, and Astronomicon’s visualization capabilities together helped them to think about tilt and seasons. After observing the pattern changing from one season to another, Betty suggests positioning themselves to a location where they can actually see the Earth tilting toward and away from the Sun [121].

121. Betty: Um, do you think you can get a picture of, not from this waypoint, but of how we can see when the axis is tilted?

122. Allen: Yes, we can do that, definitely.

123. Betty: Alright, let’s change the waypoint. Just view it from above now?

124. Allen: I thought maybe from the side. [viewing the Earth front view; Earth tilted to the left]

125. Betty: I know at one point I could see it (the tilt) moving. [watching the screen] We need to see the Sun too, where is the Sun?

126. Allen: [selecting the Sun; arrow pointing to the left] Sun’s that way [pointing to the left]

127. [Running the model, Earth keeps the same tilting direction with Sun’s changing position.]

128. Betty: Let’s look at it from the Sun. I think we may see it from there.

129. Allen: Alright. [adding a new waypoint, ‘sun to earth’; running the model.]

130. [Betty and Allen watch the changing tilt and talk about the seasons.] (Figure 3.10)

131. Allen: I mean that’s it right there. That’s whole, what causes the seasons.

The visualizations in Figure 3.10 are from the combination of the luminosity pattern, Earth’s pole, and the waypoint, ‘sun to earth’. Betty had insights on the important aspects (tilt [121] and location of the Sun [125]) for their observations in relation to the concept they are dealing with, which enabled them to systematically use the representations in Astronomicon.

- Insert Figure 3.10 about here -

Throughout the semester, the inquiry strategies of Betty and Allen became more systematic and
focused. They started making some simple predictions, reasoning through their observations, collecting purposeful data, and precisely recording relevant information about the data, such as time and waypoint. As Betty and Allen moved into the last couple of exercises, they became competent in assessing the questions and the models. Although they were not at the expert level, the way they worked on their problems showed some expert traits, such as reasoning predicatively with a working hypothesis (Anzai, 1991; Patel & Groen, 1991).

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 throughout a semester. The complex process of their development was reconstructed and exemplified within three themes: role negotiation, knowledge structure, and viewing perspectives. 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 then gradually gained expertise in modeling-based inquiry and the tool, and individually, 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 of seeing what happens toward more focused inquiries of making predictions and devising Astronomicon features to understand relationships (problem-solving strategies). Betty and Allen gradually found their roles in this team and internalized their inquiry process, as well as the procedure of building and observing models (automaticity). The gains from each week became important foundations for their performance in the following week, making their partnership stronger little by little.

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. In order to discuss a further facilitation of this partnering process, we need to look at those challenges, confusions, and immaturity of the joint learning system.

Forming a Strong Joint Learning System

The joint learning system of Betty, Allen, and Astronomicon within this lab grew strong over the semester. Each learner’s relationship with Astronomicon, however, was different. Betty decided to play different parts after going through many situations of attempting to make her own models, whereas driving Astronomicon was something that Allen never intended to give up.

Allen built an intimate relationship with Astronomicon because he controlled the whole modeling and observing process. Allen, however, was often carried away by seeing something interesting or by wondering about what he would see from different angles. Having some distance from Astronomicon, Betty, on the other hand, was able to draw Allen’s attention to bigger pictures (she constantly suggested utilizing orbital disks and viewing from overhead) and focused their activities on given tasks. Consequently, Betty came to give more significant influence on making good use of visualizations and observing from different perspectives to see patterns.

Betty and Allen, however, did not agree on their roles until the 6th week into their exercises. Betty had to deal with this awkwardness of being dependent on Allen’s modeling. Even though both successfully played their roles throughout the semester, after finishing the course, Betty commented that she felt as if Allen got to do all the hands-on stuff. Allen, on the other hand, commented that working with the partner helped him understand things better. There needs to be some guidance and support in working as partners, perhaps by suggesting alternating their responsibilities, which may give learners opportunities to look at the questions and models from different perspectives, building both intimate and distant relationships with Astronomicon at the same time.
Becoming the “partners in cognition” (Salomon et al., 1991), was found to have multiple aspects of relationships that influence learners throughout their development. Ultimately, learners should have a strong cognitive relationship with Astronomicon, thinking effectively to perform their tasks. In the case of Betty and Allen, we saw that other situational aspects were affecting their cognitive relationship, which can be seen as both a physical relationship and an emotional relationship. The physical relationship is as mainly what Allen was involved in, working with Astronomicon and being able to control the timer and to switch among views and objects, which became his automatized skills over time. This physical relationship with Astronomicon affected both their cognitive and emotional relationship. When everything was controlled smoothly, they were effectively reasoning in a collegial atmosphere; when waypoints went out of control, they became frustrated and their activity was no longer focused on their inquiry, but on figuring out what was wrong.

Betty developed her negative emotional relationship at the beginning of the semester due to several factors. Her absence on the first day of exercise 1 built a relative distance from Astronomicon when she came back and prevented her from thinking productively with it. This awkward cognitive relationship with Astronomicon and the resulting underperformance on her first report had a detrimental effect on her emotional relationship. This relationship, in return, made her even more distant physically and cognitively from Astronomicon for some time. Betty’s emotional relationship with Astronomicon, however, took a positive path when she began to have a stronger cognitive relationship with her partner and Astronomicon and became confident in her roles. She showed deep cognitive involvement when testing different factors to change the length of a day during the second day of exercise 2 and when finding ways to increase or decrease the frequency of eclipses in exercise 5.

The activities that required testing inputs (e.g., mass, distance, eccentricity) on phenomena helped Betty and Allen understand the underlying relationships of models. These activities also seemed to help them build strong cognitive partnerships by engaging them in brainstorming which parameters to change and predicting and seeing the effects. For example, Betty and Allen worked on changing the frequency of
solar eclipses for the Eclipses exercise. One of the parameters they changed was the inclination of the Moon’s orbital plane around the Earth [132-133].

132. Betty: How can we make it so that they line up more frequently?

133. Allen: We can make the inclination of the orbit of the moon zero, so it’s on the same plane of the earth... so it might make it automatically have one every time. Let’s see.

134. [Changing the inclination to 0; Running the model, the shadow of the Moon falls around the equator on Earth every time it is between the Earth and the Sun.]

135. Betty: I think it’s going to go through right in the middle every time now. So, it’s going to increase for the places in the middle and that will make it never have solar eclipses for other places.

136. Allen: [capturing] So, depends on where you are...

137. Betty: Awesome! [starting writing notes] So we just increased and decreased by changing the same thing. We are so good!

Once Allen changed the inclination value to zero, they saw the Moon’s shadow on Earth more frequently [134-135]. In thinking of what was happening by the change, Betty realized that the observer’s location on Earth would also affect how often one would see solar eclipses [135]. She expressed her pride by her claim that they changed the system to have more eclipses and fewer eclipses at the same time [137].

This kind of activity was relatively easy for the learners because they usually knew how to do it (changing one of the parameters), and any resulting effect gave them some implications (even no changing effect shows them the relationship). Providing these kinds of activities more at the beginning could build strong partnerships and make them ready for deeper inquiries.

Building Knowledge Structure

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 remembered 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 resulting effects on the visible 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. In their knowledge structure, 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, 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.

Perhaps the baseline activities should 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. For example, we could engage learners in focused activities on exploring and comparing elliptical and circular orbits. They would investigate the factors that affect the lengths of a day—not only for Earth’s day, but also for days of other planets. Learners then would have an experienced and solid knowledge structure.
Improving the Functions and Representations of the Joint Learning System

Using waypoints, one of the most important functions of Astronomicon, confused Betty and Allen for a long time. The essential factor of building and maintaining a strong cognitive partnership with Astronomicon seemed to be the control of waypoint. For the inquiry of knowledge (planetary light and motion) that is mainly dependent on the perspective of the observer, this cannot be overlooked in support of learners. Working with waypoints should be more dealt with early on so that learners can have good control over their perspectives. The only time that they learned how to use the waypoint was the first day of the class when the instructor introduced the software. Astronomicon could also provide exemplary sets of waypoints in order to facilitate learners’ understanding about the feature and to avoid the initial confusions Betty and Allen had. Beyond the examples from the software, sharing of observation techniques and interesting waypoints could be a beginning activity by the instructor or by a group who have made interesting observations. Betty and Allen made very advanced waypoints that were set up at the exact longitude and latitude locations of world cities, the Moon and Phases. Signifying and sharing these novel ways of using the tool should encourage learners to use it more creatively.

One of the critical parts of scientific understanding is to perceive the relationships among different elements of a phenomenon. Similar to scientists’ reliance on systematic representation (Anzai, 1991), learners observed and understood phenomena through the representations of Astronomicon. Their abilities to use and understand representations gradually improved as they gained more knowledge and experience (Glaser, 1996; Winn & Snyder, 1996). Betty and Allen started differentiating one pattern from the other (eclipses from new moon phases), recognizing the patterns with some expectations (changing speed on an eccentric orbit), understanding and using multiple representations of patterns (time, motion, and illumination with visualizations), and collecting better pictures to support their arguments.

The process of representing relationships is where they construct meanings from the models. The development in the representation aspects was facilitated by their development of a knowledge structure, Astronomicon usage (especially waypoints), and the focus of their inquiry. Providing more guidance to the learners for using different methods to see the relationships, which Betty and Allen became proficient
at toward the end of the semester, should then facilitate their cognitive partnership as a joint learning system.

Overture

“Did you watch the lunar eclipse last night? People were like telling me, ‘Man, you should see it!’ So I said, ‘You don’t understand. I got a program that I have to do every week. I can make a lunar eclipse every single time. I am not going to go out my way to find one.’” — Allen, during the Eclipses exercise

We saw the development process of a joint learning system that went through multiple challenges over a semester in a college laboratory class. Betty and Allen became more and more capable of engaging in scientific inquiry with Astronomicon, and in the end they became less dependent upon the tool itself and more dependent on their mental images of the inner-workings gained from previous inquiries. Knowledge, functions, and representations of the joint system came to have stronger structures as each moment of working together provided new meanings (the concept of eccentricity and its value range came to have new visual meanings), which became instruments of their further development (eccentricity became their testing factor for other concepts such as eclipses and seasons) (Dewey, 1910/1997).

Betty, Allen, and Astronomicon formed a strong partnership, which even extended to their life outside of the classroom, as we could tell from Allen’s joke on observing eclipses. Yet, with the carefully designed approach of adopting this cognitive tool into inquiry-based laboratory, Betty and Allen ran into multiple conceptual or situational challenges. In order to adopt cognitive tools in inquiry approaches and to enable learners to really think with it, we need to consider how we bring them into classrooms. One thing that was not discussed above is the time constraint (2 hours a week), which we also need to think about from the learners’ perspective and how much time they need to spend to actually engage in deeper inquiries. Allen, who liked to explore with various angles of viewpoints, once uttered, “There is like so many things you can do with this program. You can’t do it in two hours ’cause you can look at it from every angle possible.”
Through this study, we have gained a deeper understanding of the process whereby a pair of learners develop 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.

References


Table 3.1
*The participants’ misconceptions and/or lack of knowledge based on the pretest results*

<table>
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<tr>
<th>Scales</th>
<th>Orbits</th>
<th>Phases</th>
<th>Eclipses</th>
<th>Seasons</th>
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</thead>
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<td><em>Betty</em></td>
<td>Underestimation</td>
<td>- Day/night: by Earth orbit around Sun</td>
<td>- Lunar phase by the moon in and out of the Earth’s shadow</td>
<td>- Lunar eclipse can happen on any lunar phase</td>
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<td>- Their relationship with time and observed face of Moon</td>
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<td>Underestimation</td>
<td>- Rotation and revolution among Sun, Earth, and Moon</td>
<td>- Different moon phases in different places on Earth</td>
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<td>- Their relationship with time and observed face of Moon</td>
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<td>- Same face vs. Rotation (moon does not rotate)</td>
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CHAPTER 4

LOOKING THROUGH MULTIPLE LENSES:
REFLECTION ON THE METHODOLOGICAL APPROACH
IN LEARNER-TECHNOLOGY-ACTIVITY INTERACTIONS⁴

⁴ Kim, B. To be submitted to Educational Technology Research and Development
Abstract
This paper explores how we can examine learner-technology-activity interactions as we study learners, their characteristics, learning process, and learning outcomes, and how we can bring them together without isolating one from each other. The discussion is based on the reflection of the research approaches for two such studies. It intended to describe the theoretical assumptions and questions in the research on cognitive tools, to explain methodological assumptions based on them, to present the case of the research studies in answering the questions, and to provide directions for future research and practice.
Looking Through Multiple Lenses: Reflection on the Methodological Approach in Learner-Technology-Activity Interactions

Defined as technologies extending the cognitive abilities during problem solving and learning (Jonassen & Reeves, 1996), cognitive tools have been researched and had significant impacts on the scholarship of advanced learning technologies (Lajoie, 2000; Lajoie & Derry, 1993a). The computer applications described in research studies were designed or adopted as cognitive tools for learning tasks. For example, semantic network software was used to extend learners’ capabilities of organizing thoughts (Jonassen, 1993) and visualization tools of investigating scientific data (Edelson & Gordin, 1998).

The concept of cognitive tools comes from emerging learning theories (i.e., constructivism and distributed cognition) that help account for human interactions with the environment. Cognitive tools extend the domain of knowledge and performance outside of an individual’s mind. Therefore, an individual as a unit of analysis has been questioned and is no longer considered legitimate; instead, a person with environments in action is suggested to be used as an integral unit for research (Cobb et al., 1997; Hutchins, 1995; Lave, 1988; Pea, 1993; Perkins, 1993; Salomon, 1993b; Wertsch, 1991). Lave (1988) has argued for and exemplified cognitive research outside of the laboratory to capture the human interactions with environments as practiced in everyday activities. As an effort to study technology and human cognition, Suchman (1987) examined human-machine interactions through close investigation of the communications between human and machine. She explored how particular situations related to our actions and could yield productive interactions by understanding the differences between human interactions and machine operations.

Recent research on learning and thinking has also attempted to understand the relationships between individuals and technology, including cognitive tools. Conventional research approaches, however, could not easily capture the development process of learners and cognitive tools as learning partners (Kozma, 2000b). It was also often impossible to observe and report the process within a short period of time. Rigorous data collection methods are now incorporated to look at learning processes, considering affordances of technology with the learners’ corresponding interactions and learners’
development in their tool usage by changing the task complexity (Erkunt, 1998; Iiyoshi, 1999). Many of the studies on learning technologies still struggle to move beyond the exclusive focus on the individual (Karasavvidis, 2002), as they often do not necessarily address how the tools extended the capabilities of the learners as intellectual partners and how the use of the tool may or may not have entailed better (or different) learning opportunities.

Another problem with research practice on learning technologies is that fewer scholars have focused their research and discussions on the theories underlying the development and practice in education (Silverman, 2000). The self as an instrument of research makes sense of the situation with researcher’s implicit and explicit theories (Eisner, 1998). Whether explicit or implicit, all observation is selective and influenced by researchers’ theories, looking at the phenomena in particular ways; in response, theories are developed, modified, and confirmed to be more (or less) useful through continuous research (Nickerson, 1993; Silverman, 2000). Silverman (2000) suggests making our theory explicit and considering it as a toolbox for our research process, as it provides a framework for understanding phenomenon and a basis for organizing our understanding.

This paper explores how we can extend our unit of analysis to understand the learners’ extension of their cognitive capabilities, by studying characteristics, processes, and outcomes of learners together with technology, without isolating one from another. The purpose of this paper is to reflect upon the journey of the researcher to capture the complex interactions during learning with a cognitive tool in a college introductory astronomy laboratory. This paper will:

1. describe the theoretical assumptions and questions in the research on cognitive tools
2. explain methodological assumptions based on them;
3. present the case of the research studies in answering the questions;
4. and find directions for future research and practice.

Theoretical Assumptions

Theory provides direction for research. Through the lens of theory, particular aspects of occurrences in a context become significant to the eyes’ of researcher. The following theoretical
assumptions of the studies came from the theories of distributed cognition and expertise. The theory of distributed cognition emphasizes the distributed nature of cognitive activities across individuals, artifacts and representations; that is, people think in partnership with others and with tools (Kozma, 1991; Salomon, 1993b). Specifically, the interactions among individuals and tools build the distributed structure of thinking and working together. 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). Technology used in professions also partly defines expertise because experts rely on their tools for their performance (Stein, 1997).

These two theories together form a lens for research on cognitive tools. The assumptions of how to view the specific learning situation of working with cognitive tools are: 1) tools bring in specific affordances that constitute the expertise of a joint learning system within specific activities; and 2) the distributed structure of cognitive activities changes in its nature and complexity as participating individuals gain expertise in their use of tools. Each assumption will be further explored in the following subsections.

*Distributed Cognition of the Joint System*

For the purpose of research on cognitive tools, tools may be treated as bringing in specific affordances that constitute the expertise of a learner-tool joint system. The expertise of a person is developed over time whereas expertise of a tool is designed and exploited by users. Cognitive tools can be designed to take specific roles, so that three primary elements of expertise, including knowledge, functions, and representations, are distributed between learner and the tool. Knowledge ranges from widely accepted facts to abstract rules (Anzai, 1991; Patel & Groen, 1991). Functions vary from simple information search and rule execution to higher-ordering thinking and problem-solving (Ericsson & Charness, 1994; Perkins, 1993). Representations of our knowledge and perceptions can be more concrete (isomorphic) or more abstract (symbolic).

Patel and Groen (1991) categorized human expertise in three levels: *domain-independent* (general) expertise, *generic expertise*, and *specific expertise*. These levels are used to understand the roles
of tools for cognitive partnerships. The more specific a cognitive tool is, the more in-depth activities it affords covering less content variety (e.g. medical informatics); the more general it is, the more various activities and contents it allows (e.g. semantic network). The design of cognitive tools and activities for learners should then reflect the expertise level, conveying the usage of similar tools in the world as well as the expertise of the involved people. The design of a tool becomes worthwhile only because of the activities it affords, and this is considered one of the most crucial components of research on cognitive tools (Salomon, 1993b).

To understand the roles of the learner, the tool, and the activity in the performance of tasks, we need to understand the different aspects of each. Concerning these issues, research would start with questions such as, what a learner would do for learning activities in a particular situation, how particular affordances of a tool would affect the learning content and create particular kinds of interactions, and how particular cognitive capabilities of a student would facilitate engagement in particular kinds of interactions (Akhras & Self, 2002). The focus of questions should then be moved to understanding the distribution relationship of the joint system: how different components of cognitive processes and products are distributed and what affects the dynamics of distributions (Pea, 1993). Answers to these questions are important for understanding and reexaming the roles of the tools, the effects that learners have by working with the tools, and the function of specific pedagogical approaches in the classroom in order to ultimately improve the design of cognitive tools for learning.

Development of Expertise and Partnerships

With the theory of expertise and distributed cognition, we can also assume that the distributed structure of cognitive activities changes in its nature and complexity as participating individuals gain expertise in their use of tools. Through the process of learning basic competences, learners gain knowledge structure, problem-solving strategies, and automaticity for their performances (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996). Learners’ improvement in knowledge and skills not only advances the performance of the joint system but also broadens the scope of possible activities. To investigate these kinds of evolution, we should ask questions such as what kinds of changes in the
structure of distribution improve the performance of the joint system, what changes need to be made in order for learners to engage in particular learning activities, and how particular activities could lead these changes (Akhras & Self, 2002; Pea, 1993).

An interaction at a particular time is likely to result in changes to the very relationships formed for that interaction. Studies on how cognitive tools are used in relationship to learners and activities thereby require an extended time of investigation. The research questions should be able to account for many other important factors, such as the purpose and context of the activities (Karasavvidis, 2002; Wertsch, 1998). Regarding the change of relationship, we can ask questions, such as how the learner’s focus moves beyond understanding the tool and how the distribution of cognitive processes for activities changes over time within the joint system. There are countless computer programs that support cognitive aspects of task engagement, but there is not sufficient investigation regarding how students come to finally use the tool in profound ways, how students’ growing expertise in use of the tool for scientific inquiry has an impact on their development of intellectual partnership with the tool, and how those partnerships evolve over time (Akhras & Self, 2002; Karasavvidis, 2002; Pea, 1993).

Methodological Assumptions

The underlying theories for research drive the methodological approach as well as the conceptual interpretation of a study. As cognitive tools take on certain roles for learning activities, different tools for studies constituting varying lenses are needed to see the whole picture of what is investigated. The major tools of the scholar then include the underlying theories and the methods of capturing events. For studies on cognitive tools to capture the relationships between the learner and technology, primacy should be given to the on-going learning activities performed by the joint learning system. Assuming that learning occurs in a distributed manner, an individual learner can no longer be regarded as a legitimate unit of analysis (Brown et al., 1993; Hutchins, 1995; Lave, 1988; Pea, 1993; Perkins, 1993; Wertsch, 1998). For research on cognitive tools, we start with methodological assumptions that we investigate the partners, in action. The unit of analysis should be learners together with computers, and the research methods should
capture the learning events in action in order to examine their intellectual partnerships forming and evolving.

**Partners**

The extended unit of analysis includes a cognitive tool as an inseparable entity for learner capabilities. At the same time, each tool should be considered as having its own contributing qualities (Salomon, 1993b). The distributed cognition plus expertise view suggests a way to look at two kinds of completely different subjects (learners and tools) as partners of a compound system. Detailed concepts of these theories (e.g., elements of expertise structure: knowledge, function and representation) become important constructs for understanding the qualities of each. The performance of the tool, therefore, should be given a significant attention.

**In Action**

Understanding the complex nature of a distributed cognitive system requires studying it in action during the time when the interactions are actually happening—not before or after (Pea, 1993; Wertsch, 1991). The learner or the tool alone without any interaction is no longer a distributed system, even though there is a potential relationship between the two. Just as any kind of designed artifacts has intended uses for certain types of activities, educational settings usually have activities that are designed for potential relationships among interacting units to enable or promote opportunities to learn. The emergent characteristics of a learner, however, cannot be understood without taking into account his or her relationships with specific activities and tools at particular times. Research on cognitive tools should then mainly concern itself with how to capture the complex relationships and actions.

Pea (1993) suggests two ways of examining intellectual partnerships for the study of distributed cognition with technology: analytic and systemic approaches. The analytic approach focuses on examining the specific contributions made by the person and technology to the performance of a task. The systemic approach, on the other hand, examines the aggregate performance of the person-computer system as a whole entity. These two approaches can be used to address different research questions. In the following section, research studies on the joint learning systems with both analytic and systemic views
are presented as cases that explored what the distribution actually looked like and how the expertise of the joint learning system evolved.

Capturing Partners in Action: Two Studies

Our theoretical decision for research directs our attention in particular ways and, in part, decides what and how we examine the world (Eisner, 1998; Silverman, 2000). Silverman (2001) argues that choice of data type depends on our research questions, which derive from the assumptions of researchers, meaning that no one type of data is intrinsically better or worse than any other type of data. He further exemplifies his argument with a research topic of “street”: if the questions are “1) how traffic flows on a street, 2) how people cope with rush hours, 3) how streets form geometric shapes, and 4) how people queue/organize their movements on a street,” then the data can be collected with “1) official statistics, 2) interviews, 3) observations from a tower, and 4) observation/video at a street level” (Silverman, 2001, p. 194). Research questions, therefore, help us identify what is important to capture using what kind of method.

In order to examine what the distribution actually looks like and how the distributed system develops, it is important to capture the workings of all the partners (learners and the cognitive tool) of a joint learning system. Jordan and Henderson (1995) suggest using multiple cameras to effectively capture interactions involving other objects, especially the computer, so that the researcher can view and analyze how the computer responds to what people do and how this plays out in their interactions. Various data collection methodologies are now incorporated to capture the interactions between learners and technology, such as videos, logs of user interactions, and recordings of computer screens in addition to observations and interviews (Barab, Hay, & Yamagata-Lynch, 2001; Goldman-Segall, 1998; Kozma, 2000b). Data analysis methodologies for these studies, such as discourse analysis and interaction analysis, are focused on the impact of the features of learning environment on the reasoning and understanding of learners (Barab et al., 2001; Jordan & Henderson, 1995).
Studies to Test Assumptions

The research questions for cognitive tools should focus on the roles of tools and learners as cognitive partners within context as well as on their partnering process, based on the theoretical and methodological assumptions above. Answers to such questions should help us to improve how we design and utilize cognitive tools. As a research tool, theory guides the close examination of cognitive tools. With the theories of expertise and distributed cognition, we ask questions such as, what affordances tools should have, in what areas of expertise, in what levels, with what kind of structures, and what roles we expect learners to play in the structure of distributed cognition. Extended observations of learners using cognitive tools should inform the process in which the learners and their tool become complementary cognitive partners.

The participants of the studies to test two theoretical assumptions were learners working with a 3D modeling software (Astronomicon) in a college astronomy laboratory course. Together, they were participants of the studies making up the structure of cognitive activities. Therefore, the focus was neither solely on the students (their knowledge gains) nor on the computer (its effectiveness), but on the joint system (the process and product of distribution). Learners with a cognitive tool are considered as different beings who think differently from the selves without it. The tool also becomes a different instrument when used by a certain individual. The tool by itself only means an entity of various programmed functionalities. It is not until a particular learner uses it that those functionalities become meaningful for certain cognitive activities.

Testing the Assumption of the Distributed Cognition of the Joint System

The first study was focused on the design issues of a cognitive tool by examining and comparing interactions across different groups of learners engaged in common activities. The main purpose was to examine the roles of a cognitive tool and learners and the functions of a specific pedagogical approach in their tool use, in order to improve the design of the collective learning system including learner, cognitive tool, and learning activity. The idea was that the tool (Astronomicon) and the way it was used in the astronomy lab could promote appropriate design and use of a cognitive tool for scientific inquiry.
Testing the Assumption about the Development of the Cognitive Partnership

The study for this assumption was focused on the longitudinal application of the same cognitive tool by observing one group of learners interacting with it over an entire semester. The intent was to develop a deeper understanding of the process whereby learners become more capable of engaging in scientific inquiry with a cognitive tool. The fundamental purpose of gaining knowledge through this study was then to improve practice in adopting cognitive tool-enhanced inquiry-based approaches. The assumptions about the designed approach of the research setting (astronomy laboratory) were that the processes and products of learners’ activities using the tool (Astronomicon) resembled those of scientists’ practices and that its curriculum was designed to support the process of gaining expertise in the use of the tool and scientific inquiry.

Researching the Designs in Action

Researchers have adopted alternative approaches in order to understand this particular kind of complexity. Akhras and Self (2002), for example, proposed modeling the situations and activities, the learning interactions and processes, and the affordances of technology for the design of intelligent tutoring systems to move research beyond the cognitive processes of individuals. Researchers now incorporate data collection methodologies that capture the interactions between learners and technology, such as videos, logs of user interactions, and recordings of computer screens in addition to observations and interviews (e.g., Barab et al., 2001; Goldman-Segall, 1998). Data analysis methodologies also focus on the impact of the features of learning environment on the reasoning and understanding of learners, such as discourse analysis and interaction analysis (e.g., Barab et al., 2001; Jordan & Henderson, 1995). Research on cognitive tools that intends to contribute to both design and practice should adopt these alternative approaches in order to gain a more complete understanding of the multifaceted interactions among learners, tools and activities in context.

The major source of capturing the complexity of context for the studies was digital video recordings. Figure 4.1 illustrates the overall research process with the main tools, including the researcher self and the video as capturing and analyzing methods. The comprehensive approach to the research on
cognitive tools starts from creating and/or understanding the software design, the curriculum design and the research design.

- Insert Figure 4.1 about here -

The researcher(s) (or research team) and the instructor set up the classroom to provide an ideal learning and research environment to actualize the designs, including computers with the software for learners and video camera set-up for research. During these processes, expectations are formed regarding the experiences of learners, instructor and researchers in the classroom and the process of video data collection. Participation in this context helps the overall understanding of how the activities are actually carried out, and during which the researcher start to shape interpretations of the classroom dynamics and expectations of the learners interactions in the videos. When watching the video the detailed interactions of the joint learning system are finally revealed. Through the continuous process of being in the classroom and watching the videos over time, researchers also observe the changes that learners go through. The interpretations of researchers should provide implications for the improvement of the original designs.

Understanding the Designs through the Theoretical Lens

The current designs come from a reform effort for an undergraduate astronomy laboratory course. The main characteristics of this project include the implementation of inquiry-based pedagogical approach and a 3D model construction tool called Astronomicon. This course intends to enhance students’ understanding of astronomy, specifically addressing basic topics of orbits, time, phases, eclipses, and seasons.

The designs of the tool and the activity are also reinterpreted and reorganized with the specific lens provided by researcher’s theoretical assumptions. The researcher’s assumption that distributed cognition is structured in the same way that expertise is structured (with knowledge, functions, and representations) gives a framework by which to understand the designs that constitute the potential joint learning system. By understanding the capabilities of the tool and the conditions of the activity, we can see the potential distribution of learning performance.
**Tool.** Astronomicon (see Figure 4.2) is a computer modeling tool for astronomy learning, especially planetary motion and light. Learners build and simulate their own models of solar systems within a three dimensional (3D) environment. The models that learners create using Astronomicon can be used not only as surrogates of real world solar systems but also as experimentations of non-existing systems.

- Insert Figure 4.2 about here -

The potential roles of this cognitive tool in learning activities are implied by its embedded knowledge, functions, and representations described in Table 4.1. The important knowledge of Astronomicon is the underlying physics rules in order to configure relationships among relevant measures (e.g., masses and distance between objects). Astronomicon executes the rules as users provide inputs, such as producing and running models, and processes 3D images of models, keeping the ratio of physical values, such as sizes and distance. For example, Astronomicon must perform the rules to configure the 3D space in order to produce a waypoint (a viewpoint defined by observer location and target direction) and 3D images to display the view from it. Figure 4.2 shows the waypoint set-up to view from the Earth to the Moon.

- Insert Table 4.1 about here –

**Activity.** The pedagogical approach used in this project focuses on computer modeling to investigate phenomena that are impossible to understand without such technology, through which students engage in the model-building practices to try out their hypotheses, methods, and strategies using the similar processes of experts. The designed activity is then thought to condition knowledge, functions, and representations to be used for learning activities. The knowledge that is expected to be used and gained through each activity would be relevant to the provided inquiry questions. In the example in Table 4.1, learners are expected to have a deeper understanding about the cause lunar phases through an exercise. The expected functions are mainly the decisions that learners need to make to build and run their models, such as making a waypoint, looking from the Earth to the Moon. The representations to be used
are often implied by the questions, such as ‘what causes lunar phases?’ In this case, the learners need to observe the Moon going through the phases from the Earth.

*Video-Based Research, Adding another Lens*

In choosing the data collection method, it is important to consider what kind of data will give us an explanation of structure and meanings of phenomena from within our perspectives (Silverman, 2001). To account for phenomena from the perspectives of distributed cognition and expertise, the data should give insights into the processes and structure of cognitive activities. Video data can provide rich and detailed descriptions of research situations and have been used in many different ways to serve the purpose of each study (e.g., Barab et al., 2001; Goldman-Segall, 1998; Schoenfeld, 1992; Stigler, Gallimore, & Hiebert, 2000). Using video, we can capture and continuously access non-verbal cues that are difficult to record and represent through observations and audio recordings, such as gestures, body languages, and uses of environment (Emmison & Smith, 2000; Roschelle & Goldman, 1991; Silverman, 2000).

The repeated inspection and analysis of video with simultaneous view of recordings of both students and the computer are critical in order to understand how students interact with the tool and to examine how their use of its functions changes. This kind of investigation is very hard to do without digital technology to record and play multiple recordings (Jordan & Henderson, 1995). Research has adopted a complex digital data collection and analysis system, called Integrated Temporal Multimedia Data (ITMD) research system (Hay & Kim, in press), for the in-depth investigation of the learning process. With this system, the activity of each group (working in pairs), screen captures of computer activity (one laptop computer for each learner) and voice of each participant are recorded, stored, and retrieved together in digital formats (see Figures 4.3 and 4.4).

- Insert Figures 4.3 and 4.4 about here -

We impose our way of seeing events on where we place the camera and in what angle we point to the participants. The diagrammed data collection set-up in Figure 4.3 then embodies special meanings for learner-tool-activity interaction research. It has given significance to each partner of the joint learning
system, including learners, their computers, and contextual influences at the class level, by recording them separately. This enables the research to extend its unit of analysis and account for the contributing qualities of each participant. At the same time, it emphasizes the observation of the details of events and interactions in action by providing access to multiple camera views, actual context, conversations of learners, and interactions with computers.

- Insert Figure 4.3 about here -

Video as a Research Partner (In the Context)

Even though video cameras capture the interactions of learners, video researchers emphasize field work for proper contextualization during analysis and suggest continuing it throughout the video data collection (Jordan & Henderson, 1995). As Silverman (2001) points out, “no data are ever untouched by human hands (p.159).” A video camera reflects our expectations and interested observations as the selective position and angle of camera affect the view of recordings. In addition, a video camera cannot capture everything that happens in the classroom and cannot build relationships with students by replacing researchers.

The video data need to be collected with the researchers’ observational data at the same time for a couple of reasons. First, the researcher makes video data more complete by observing and recording contextual information and interacting with participants. Second, video recordings also complement the researcher’s limited observation capabilities, because the researcher can only give selective attention to what is happening in the classroom. The roles of the main research tools (the researcher self and the video camera) in the context are therefore extremely important for the research process.

A researcher’s observation is likely to be shaped by perspectives that reflect his or her expectations (Crotty, 1998). In dealing with video data, this is somewhat necessary to handle a large number of data sets and to focus the analysis toward answering the research questions. Similarly, Jordan and Henderson (1995) point out the importance of being present in the environment and keeping notes to indicate the times that need to be examined more closely later with the video. As Goldman-Segall (1998) puts it, the video and researcher then become research partners that share different responsibilities.
The video in the current research was responsible for capturing the detailed interactions and thought processes. Ericsson and Simon (1993) recommend recording verbal reports of participants’ thought processes when their actions actually occur. The way that the lab and the cameras are set up in this particular setting allows for recording verbally expressed thought processes with their associated actions, which naturally occurs by working in pairs. Researchers, dependent on the video, can focus their observation at a higher level, not to capture the details of interactions, but to describe the basic flow and major episodes of each class. They also have more freedom to make spontaneous thought experiments and descriptions about learners without worrying about description being too filtered through the eyes of a researcher.

*Context, Video, and Reality (Working with Video Post-Event)*

Analysis and interpretation start during the data collection process when a researcher begins attending to certain places and occurrences in the setting and jotting down notes. Whether conscious or not, researchers analyze what is happening with some general themes that originate in their research questions and theoretical assumptions (Miles & Huberman, 1994). In this context, researchers bring a certain level of interpretation to the video, anticipating what they would see through the lens of the camera. The video, however, embodies complexities, some of which were not even accessible to the researchers in the actual setting. The detailed interactions of the joint learning system are finally revealed through the video, which often turn out to be different from the expectations.

Using video technology for research projects is known to be cumbersome, time-consuming, and expensive compared to other means, such as notepads and audio recorders (Laws & Barber, 1989; Roschelle & Goldman, 1991). In spite of its costs, the video-based approach is becoming more and more widely used, perhaps because of its richness. The contextual richness of video data provides a channel to investigate the ambiguous nature of learning, adding more complications to research as the participants’ actions, facial expressions, and other contextual information are available for examinations (Goldmana-segall, 1998; Silverman, 2000).
The primary data reduction comes from the assumptions and expectations (not from the quantification of reoccurring instances) (Miles & Huberman, 1994). Using the segmentation ability of the Integrated Temporal Multimedia Data (ITMD) research system, the two-hour period of the group work was segmented into meaningful chunks (these are called ‘Nodes’ in ITMD). Figure 4.4 is the display window that simultaneously plays multiple streams of video data. Figure 4.5 shows a part of the ITMD analysis system interface with the list of nodes, which provides a doorway to the video observation and coding page (Figure 4.6). Each node is then a segment that contains meanings that guide further analysis of the workings of the joint learning system. Table 4.2 is information extracted from parts of nodes from the lab period when learners engage in an inquiry question, “What causes lunar phases?”

- Insert Figures 4.4, 4.5, and 4.6 about here -

- Insert Table 4.2 about here -

The important thing to note from this table is what each column means to the researcher in relation to her assumptions. First, nodes are sequentially organized, maintaining their temporal positions within the timeframe. In many video-based approaches with their specific research purposes, video clips are fragmented for the components that require special attention or clustered into chunks indicating similar themes that happen multiple times throughout the event. Organizing the interactions in a sequential manner becomes important when examining the joint learning system in action because the present action and its consequence would no longer be explicable without understanding its precedent and subsequent actions (Hutchins, 1995).

Second, examining the participants within a node reflects the assumption of the joint learning system and its extended unit of analysis for research. The learners with environment while in action become a legitimate unit for the research (Salomon, 1993). Assuming that computers are potential participants at all times within this classroom setting, only human actors are indicated as participants. In Table 4.2, Betty and Allen were partners in a group and the instructor participated in this group from time to time. The person who was first listed in the each node is the one who had the major influence on the transitions from one node to the other. When the instructor is listed alone, he was talking to the entire
class, which made every learner in the classroom a potential participant of that time (some attended fully to his account and others partially).

Third, the decisions on where to set the boundaries between nodes were based on shifts in activity. The arbitrarily chosen temporal boundaries of events can make things even more incomprehensible (Hutchins, 1995). Considering the importance given to the design of activities for the interactions of the joint learning system, the segmentation based on the learners’ involved activities gives more meanings to each node. The activities could be divided in multiple levels, some obviously by design. In the example in Table 4.2, the whole day was devoted to question Two in exercise four (students briefly move through question One: the definition of phases as they remembered it), and they worked on modeling three theories (a, b, and c; the explanations of lunar phase phenomenon) to answer the question. The example began with the instructor’s explanation about the question and each theory (node one, three, and four), and then Betty and Allen moved onto question One and the first theory of question Two.

The chunks at the theory level were still pretty broad, depending on the complexity of their modeling and observations. On this particular theory about lunar phases (two-a: Phases of the Moon are caused by a shadow from the Earth), Betty and Allen initially spent about 40 minutes. The smaller chunks of activity below the theory level were then mainly indicated by the cues that learners provided in relation to their inquiry processes (Jordan & Henderson, 1995). The cues were associated with their actions and words, such as looking at and reading a question or a theory from the exercise sheet, deciding to ask a question and calling the instructor, being satisfied with their observations and saying, “okay, now we need to take pictures of each phase,” and the instructor looking over to their screen and conversing with them.

Finally, some notes were taken when indications more than time, participants, and activity were necessary to understand the overall picture or to mark the importance of certain incidences. For example, Betty’s class notes for the answer to the first question indicated her misconception relating to the instructor’s lecture. The researcher made a note of it in order to give attention to Betty’s class notes for further analysis (see Notes column, Node 3 in Table 4.3).
Understanding the Distribution

Theories are most valuable when they are fully applied within research and provide explanations for phenomena, and one should look for the interrelations among (theoretically defined) elements by analyzing data (Silverman, 2001). The theories of the researcher play critical roles in this interpretation stage of research. In order to understand the workings of this intellectual partnership for the study, the basic distributed structure of joint learning system, including learners, Astronomicon, and the other set-up of Astronomy lab (the activity and the instructor), is identified with three primary elements of expertise: knowledge, functions, and representations. These elements are analyzed to understand the different roles that learners, tools, and activity design play to perform certain tasks (the analytic approach).

At a detailed level, interactions can be analyzed as conversations: human’s conversations (or communications) with computer. This micro level of analysis allows us to identify how processes of interaction are structured beyond what kinds of interactions occur (Erickson, 1992). The conversation analysis for interactions with a computer should start with identifying the sequences of relevant interactions, examining how students and computer take on certain roles or identities through their interaction, and then looking for particular outcomes in the interaction (Silverman, 2001).

The overall structure of the distributed relationship was developed through identifying the interplay between the theories and the actual interactions (see Table 4.3). The role of instructor partly represents the role of the activity, as he was the main source of orienting learners to each activity and conveyed ways to approach problems. On the learners’ part, knowledge, functions, and representations of the two learners are treated as one in the table. Their base knowledge often includes their misconceptions about certain phenomena, in addition to the basic astronomy knowledge.

- Insert Table 4.3 about here -

The functions of learners are particularly related to their decision-making throughout the inquiry process. These functions affect how the software is used and how the activity is carried out, and at the same time, they are affected by the design of the software and activity. Learners find basic information for investigating the problem situation, make decisions about how to approach the problem and how to
create models, and recognize the patterns of phenomena. The representations of learners tell what kinds of knowledge they have, what kinds of functions they are performing, and how they represent their understanding to share with others. They are the main resources for the researchers to understand the intellectual partnerships, because we can understand their thinking and learning only through some kind of representations.

Astronomicon embodies knowledge, functions, and representations that extend the capabilities of learners. Astronomicon visualizes bodies with learners’ inputs, runs the model with the underlying rules, and provides various investigation supports. The functions of Astronomicon have to be utilized by the learners in order to create representations of testing phenomena. How this complex design of the joint learning system works to enable learners to have deeper inquiry is the main focus for this framework.

In order to discover how these various components play out within the joint learning system, one group was analyzed in depth, and then four more groups were compared with it. Table 4.4 exemplifies how a small activity of making a waypoint could be performed together as a joint system. To observe the illumination pattern of Athens, Georgia, learners start making a waypoint (Table 4.4: four, five, seven, & ten) with the limited provided information (one; thirty four north) and direction (six) represented on the exercise sheet (eleven). They look from the waypoint (eight & fifteen) and realize that they do not see Georgia because no longitude value was entered (nine & fourteen). They then find the longitude value (eighty three west) of the city from the web (two, three, & twelve), and input the value input the waypoint (seven). Later, they collect some images from Astronomicon to report their observations (thirteen, fourteen, & fifteen).

This kind of analysis provides a deep understanding of the distributed structure of the joint learning system. At the same time, it becomes much more apparent to us where we need to improve among those components in order to enhance the collective performance of the joint learning system. For example, for learners to start with more information the exercise sheet could either include the longitude value of Athens or suggest finding the value.
Understanding the Development

In the second study, the three primary elements were no longer dissected to find out about the roles of each, but the overall performance of the joint learning system was emphasized. Learners came into the setting where the curriculum and the software above were uniquely combined. They activated the potential cognitive relationships and started developing the joint system as they were engaged in learning activities. These roles and relationships evolved as the learners developed their knowledge base and strategies, and the complexities of activities increased.

In order to understand the development as a joint learning system, the systemic approach is more appropriate. For the progression of each exercise, the three primary elements of expertise (knowledge, functions, and representations) were examined to see the pattern of development throughout the course as to how knowledge was constructed and structured, how different functions were developed, and how well representations came to be used (the systemic approach). Gains from each day make the partnership of the joint learning system stronger.

The analysis table, therefore, transitions to a somewhat simplified but broader version that accounts for the performance of the joint learning system as a whole (Table 4.5). The main development components are classified based on the elements of expertise structure, considering the indicators of gaining expertise: knowledge structure, problem-solving strategies, and automaticity (Keating, 1990; Schneider, 1993; Winn & Snyder, 1996). During the 3D modeling process, learners transform their factual knowledge from lectures and textbooks into an experienced knowledge that is situated in a coherent structure because the knowledge is used and understood within their activities.

- Insert Table 4.5 about here -

The way learners use the tool and how much cognitive effort is required to use it change every week. The inquiry process and strategies that learners use for the tasks also develop as they are engaged in a series of scientific inquiries. One of the important aspects of scientific investigation is recognizing. With the modeling activity in this particular learning situation, learners should be able to perceive visible patterns of phenomena, number patterns such as time and distance values, and visualize invisible patterns
such as temperature. Learners use various waypoints and visualization tools in Astronomicon. How to represent the patterns and relationships in a summative format that is easy to see and understand is an equally important role of learners.

For this study, the interactions of one group were analyzed for the entire semester (fifteen weeks / thirteen weeks of video recordings). In the example of exercise Two (Timekeeping/Day and Night) in Table 4.5, learners were engaged in inquiry activities for two weeks. The signs of progress as well as those of struggles they exhibited over two weeks were reconsidered as their development from one exercise period for analysis. As learners continuously moved from one exercise to another, the connections between their interactions began to reveal themselves. For example, after gaining knowledge about the relationship between mass and orbital rate by seeing an unexpected result from their rather random testing (second line, Knowledge column in Table 4.5), mass became their favorite testing variable for some time.

The systemic analysis on the performance of the joint learning system provided a profound understanding about the development process, because the foundations and consequences of their learning and actions were revealed through this research. The incidents that helped or hindered the development of the joint learning system could be identified in order to strengthen or modify certain activities or tool features. For example, for learners to have more ownership over certain concepts (like mass and orbit in Table 5), we could try giving more chances to explore various concepts of their choice.

Implications for Research Practice

Researchers in a context are active learners who construct meanings with and about participants, and about their learning (Kelly & Lesh, 2000). The research process (researcher-researcher tools- research activities) is somehow parallel to the learning process (learner-cognitive tool-learning activities). As cognitive tools take on certain roles for learning activities, different tools for research constitute varying lenses to see the whole picture of what is researched. The major tools of the researcher then include the underlying theories and the methods of capturing events. From the discussions about the assumptions and research practice, several implications for future research on cognitive tools can be summarized as below.
Implication 1: Research Questions should be based on the Theoretical Assumptions About Cognitive Tools for Learning

Researchers in some sense engage in very similar kinds of thinking processes to those of learners. Resembling learners’ scientific thinking for inquiry, their reasoning comes between their continuous observations, constantly testing and connecting with their theories and making inferences based on them (Dewey, 1934/1980). The practice of research, therefore, should be theoretically rich and integrated throughout the process.

This article introduced theoretical assumptions and relevant research questions based on the theory of distributed cognition and expertise for research on cognitive tools for learning. The questions to examine the distributed structure and its development should be continuously asked in order to improve and research on cognitive tools, as well as test and validate our assumptions about learning with them. More understanding is needed on the relationship between technology, design and learning for further development on our practice, theory and research, by adopting research methods that can take those relationships into account. (Kozma, 2000b).

Implication 2: Methodological Approaches Should Consider How to Better Test the Assumptions

Human cognition engaged in interaction with computer technology should deal with other dimensions of complexity in the context, which makes it harder for researchers to conduct rigorous observations. In addition to the messiness of the real context, research has to account for the new addition of technology and the changes introduced into the learning context due to its adoption, such as the role of technology in curriculum and assessment (Kozma, 2000b). The cognitive processes of learners as well as processes of cognitive tools are all entangled with other components of the context, but are not easily revealed to observers. Hutchins (1995) discusses the open nature of some tools that directly reveals the cognition of a task performer, e.g., when the person is drawing a chart on a paper. Computers, especially those designed to perform cognitive tasks distinctive from learners’, however, are not meant to reveal cognition of learners, but to interact with it. They even have their own computational processes that are important for the accomplishment of tasks, which researchers need to take into account for their research.
Research based on the two assumptions, therefore, requires a very comprehensive approach that can account for this multifaceted complexity.

As means of capturing the distribution and the development of the joint learning system, the studies exemplified in this article used video-based approach. Using digital video, interactions of multiple participants including learners, computer, and instructor could be captured with contextual information for the in-depth investigations about the roles of each as well as the development of the collective system. In order to understand the contributions that a cognitive tool makes to the cognitive partnership, its detailed process should be given attention equivalent to the cognitive process of learners.

Implication 3: Theoretical Interpretations of Interactions Should Provide Implications for Practice

Computer-based analysis is now widely used to handle the rich narratives of video data, with which researchers can start with rough coding, maintaining connection with actual scenes and then progressing to more in-depth analysis and transcription for the important parts (Roschelle, 2000). In the research process describe here used a similar approach of doing a terse and selective coding during the initial video analysis. ITMD analysis system was used to segment video, to handle the mass of data, and then to revisit specific clips for further analysis and transcribing.

The interpretations of researchers should provide feedback to the original designs and how they are used in classrooms. Both analytic and systemic approaches of studying joint learning systems provide important implications to practice, targeting different aspects of learning experience. Through the first study to map out the distribution structure, it was found that the way the activities were carried out by the joint learning system are the most important factor for a successful learning experience. By looking at how the relationship is structured and carried out by the participants of the joint learning system and comparing among groups, it was possible to find the parts that made their learning performance especially successful, atypical, or awkward. The fundamental causes of the problems were interrelated with each other, and the parts that needed enhancement could be easily identified, whether they were for the design of the activity or the software.
In the second study, the development process of a joint learning system was observed over a semester. Betty and Allen became more and more capable of engaging in scientific inquiry with Astronomicon, and in the end they became less dependent upon the tool itself and more on their mental images of the inner-workings gained from previous inquiries. Knowledge, functions and representations of the joint system came to form a stronger structure, as each moment of working together provided new meanings and further development. It was found that all the successes as well as challenges they had were interrelated throughout the semester, and that each success or challenge had its own individual history. Why the learners interacted in a particular way could not have been explained without considering their previous actions. The result of this approach indicated that providing the inquiry activities that support for their development in the early stages could facilitate the intellectual partnerships between learners and technology.

The Interplay: Theory and Research

The interplay between theory and research was considered in this article. The concepts are derived from the theories of distributed cognition and expertise, and detailed knowledge is derived from practice, possibly changing the meaning of the preconceived concepts. Through these two research approaches, we see our theories and assumptions come into play. They are no longer theories that have only ambiguous meanings in our head, but are instead alive in our world by seeing the learning process distributed among learners and technology and cognitive relationships evolving throughout the research process. Allen, one of the research participants commented on his change in thinking of astronomy:

…I mean, how big the solar system is, how far away everything is from each other, and the orientation of where everything is … if you look up at the moon, you don’t really think about it. But when you actually have to put in the distance, the radius, the mass, and everything, it gives you… not really more of an understanding, but… you are relating it to what you know, I guess… it’s hard to explain. Like, you don’t really pay attention to it until you actually see it happen. And it makes you realize, ‘Wow, the Earth is really far away,’ or the Sun is really that massive and you can’t make the Earth that much massive,
otherwise it just throws everything off. You read it in textbook and it tells you that, but
when you actually see it… I think it’s pretty helpful…

Allen’s new perspective on the solar system has the living mental images of the planets interacting in the
software. By layering theories deeply into our research process, we can enliven our perspective on them,
ultimately being enabled to see something important for our research and development.

This article also discussed various components constituting the process of research on learner-
technology-activity interactions, through the reflection of the two studies conducted by the author. The
video data were essential to the studies. The cognitive relationships the learners build throughout the
semester as a joint learning system are almost impossible to capture in the context. The other kinds of
relationships, such as emotional (frustrations and excitements) and physical (who drives the computer and
the troubles running into) relationships were often more available to the eyes of the researcher, which can
be important data for other kinds of research agenda, but only provides background information for the
present one.

The learning designs and research designs that involve technology, however, are vulnerable to the
focus on their appealing surface features. As interested individuals in technology, we often overlook the
meanings and reasons for using them. We need to look deeply upon the assumptions that we impose on
our designs for our research. By doing so, the result of the research will provide more valuable
information to researchers to advance the theories and methodologies for research practice, and
practitioners in the field to better adopt the advanced approaches.

References

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processes and affordances. *Instructional Science, 30*(1), 1-30.

(Eds.), *Toward a general theory of expertise* (pp. 64-92). New York: Cambridge University Press.


<table>
<thead>
<tr>
<th>Knowledge</th>
<th>Tool</th>
<th>Example</th>
<th>Activity</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rules embodied in the software</td>
<td>Defined</td>
<td>Three-dimensional configuration of the space</td>
<td>Given information; Required information; Expected understandings</td>
<td>Cause of lunar phases</td>
</tr>
<tr>
<td>Operations performed with user inputs</td>
<td>Function</td>
<td>Producing waypoints</td>
<td>Basic decisions to be made (how to create models; what to look for in models)</td>
<td>Waypoint: from Earth to Moon</td>
</tr>
<tr>
<td>Images processed with user inputs</td>
<td>Representation</td>
<td>Modeled reality from specific viewpoints</td>
<td>Expected observations and visualizations to be used</td>
<td>The Moon going through phases seen from the Earth</td>
</tr>
<tr>
<td>Node (Start-Stop)</td>
<td>Participants</td>
<td>Activity</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>----------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>1 (00:45:00-00:47:30)</td>
<td>Instructor</td>
<td>#2</td>
<td>For the performance of this exercise, would the performance of Group 4 and 6 be affected by their work in exercise 3?</td>
<td></td>
</tr>
<tr>
<td>3 (00:47:30-00:55:23)</td>
<td>Instructor</td>
<td>#2-a</td>
<td>See, Betty's note (she has a misconception of shadow causing the phases)</td>
<td></td>
</tr>
<tr>
<td>4 (00:55:23-00:59:16)</td>
<td>Instructor</td>
<td>#2-b &amp; c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (00:59:16-01:05:14)</td>
<td>Allen</td>
<td>Betty</td>
<td>#1 and #2-a</td>
<td>Betty is trying to figure out the definition whereas Allen is modeling. Not sure what Allen is looking to get the numbers.</td>
</tr>
<tr>
<td>6 (01:08:42-01:11:59)</td>
<td>Betty</td>
<td>Allen</td>
<td>#2-a Moon Period</td>
<td>Figuring out the 2-a Moon period</td>
</tr>
<tr>
<td>7 (01:11:59-01:12:28)</td>
<td>Instructor</td>
<td>#2-a Moon Radius</td>
<td>Suggesting approximate radius value</td>
<td></td>
</tr>
<tr>
<td>8 (01:12:25-01:15:13)</td>
<td>Allen</td>
<td>Betty</td>
<td>#2-a Moon Radius</td>
<td>Viewpoints: Earth to Moon Overhead view of the Moon</td>
</tr>
<tr>
<td>9 (01:15:13-01:15:48)</td>
<td>Instructor</td>
<td>#2-a Viewpoints</td>
<td>Emphasizing Earth to Moon observation</td>
<td></td>
</tr>
<tr>
<td>10 (01:15:48-01:22:21)</td>
<td>Allen</td>
<td>Betty</td>
<td>#2-a Viewpoints-Radius</td>
<td>Viewpoints: m to moon (Allen) earth to moon (Betty) overhead view of the moon (Allen)</td>
</tr>
<tr>
<td>11 (01:22:21-01:25:18)</td>
<td>Instructor</td>
<td>Betty</td>
<td>#2-a Moon Radius</td>
<td>Figuring out Moon radius Viewpoint: Earth to m</td>
</tr>
<tr>
<td>13 (01:27:20-01:32:14)</td>
<td>Betty</td>
<td>Allen</td>
<td>#2-a Moon Phases</td>
<td>Allen is confused about the set of phases. He keeps talking about 4 sets counting each from new to full or full to new</td>
</tr>
<tr>
<td>14 (01:32:14-01:32:35)</td>
<td>Instructor</td>
<td>Allen</td>
<td>Betty</td>
<td>#2-a Moon Phases</td>
</tr>
<tr>
<td>16 (01:37:51-01:40:08)</td>
<td>Betty</td>
<td>Allen</td>
<td>#2-a Claiming reasons</td>
<td>Betty talking about and writing down about why this one is not real</td>
</tr>
</tbody>
</table>

Note. This segments information was extracted from the nodes in Figure 7. The detailed logs and scripts with time marks are excluded.
Table 4.3
The distributed structure of the joint learning system using Astronomicon within modeling-based inquiry (MBI) pedagogy

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intended knowledge usage:</td>
<td>Background or constructed knowledge:</td>
<td>Knowledge embodied in the software:</td>
</tr>
<tr>
<td>- Questions/theories</td>
<td>- Prior knowledge and misconceptions</td>
<td>- Modeling input interface</td>
</tr>
<tr>
<td>- Concepts</td>
<td>- Collected information from textbook, website, instructor, existing model</td>
<td>- Relationships among different parameters</td>
</tr>
<tr>
<td>- Required information</td>
<td>- About tools</td>
<td>- Three-dimensional configuration of the space</td>
</tr>
<tr>
<td></td>
<td>- How to model</td>
<td>- Levels of system complexity</td>
</tr>
<tr>
<td></td>
<td>- How to observe</td>
<td></td>
</tr>
<tr>
<td><strong>Functions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guidance on inquiry process:</td>
<td>Executive functions and higher-order thinking:</td>
<td>Software performing functions:</td>
</tr>
<tr>
<td>- Modeling</td>
<td>- Deciding on what to do, what to input, what features to use</td>
<td>Rule executions with learner inputs</td>
</tr>
<tr>
<td>- Observation</td>
<td>- Choosing perspectives</td>
<td>- to create models</td>
</tr>
<tr>
<td>- Collection</td>
<td>- Recognizing patterns</td>
<td>- to change the perspectives</td>
</tr>
<tr>
<td></td>
<td>- Matching the observations with their knowledge</td>
<td>- to control times</td>
</tr>
<tr>
<td></td>
<td>- Deciding what pictures and numeral values to collect</td>
<td>- to visualize relationships</td>
</tr>
<tr>
<td><strong>Representations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provided materials:</td>
<td>Learner explored materials or produced artifacts:</td>
<td>Software processed representations:</td>
</tr>
<tr>
<td>- Textbook</td>
<td>- Websites / datasheets</td>
<td>- Models</td>
</tr>
<tr>
<td>- Exercise sheet</td>
<td>- Notes (drawings, data records, observation records, etc.)</td>
<td>- Planets</td>
</tr>
<tr>
<td>- Websites</td>
<td>- Images from viewpoints</td>
<td>- Waypoints</td>
</tr>
<tr>
<td>- Notes on the board</td>
<td>- Reports</td>
<td>- Abstract visualizations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Symbols</td>
</tr>
</tbody>
</table>
Table 4.4
Observing Athens, GA

<table>
<thead>
<tr>
<th>Activity/Instructor</th>
<th>Learner(s)</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Athens latitude: 34 N</td>
<td>2. Way to locate city on globe from the web</td>
<td>4. Waypoint interface</td>
</tr>
<tr>
<td>3. Athens longitude: 83W</td>
<td>5. Latitude/longitude mapping</td>
<td></td>
</tr>
<tr>
<td>6. Look at Athens on Earth</td>
<td>7. Making and modifying the waypoint</td>
<td>10. Rule executions with inputs to create the view from the specific place</td>
</tr>
<tr>
<td>8. Looking from the waypoint</td>
<td>9. Judging the waypoint position</td>
<td></td>
</tr>
<tr>
<td>13. Images from the waypoint</td>
<td>15. Waypoint looking at Athens, GA</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.5

*Development components of a joint learning system*

<table>
<thead>
<tr>
<th>ex2</th>
<th>Knowledge</th>
<th>Functions</th>
<th>Representations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day/month/year;</td>
<td>Timing and observation;</td>
<td>Seeing from above;</td>
</tr>
<tr>
<td></td>
<td>Mass-gravity-orbital rate;</td>
<td>Recording data and observations;</td>
<td>Same waypoint</td>
</tr>
<tr>
<td></td>
<td>Mass-day length;</td>
<td>Data collection process;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>New moon</td>
<td>Making predictions</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waypoint control;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comparing observations</td>
<td></td>
</tr>
<tr>
<td>Lacking</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Progress made*
Figure 4.1 The process of video-based research on the learner-tool-activity system
Figure 4.2 Astronomicon: Viewing from the Earth to the Moon
Figure 4.3 Classroom set-up
Figure 4.4 Betty and Allen on 10/06 engaged in an activity

Note. This video observation interface of the ITMD system is customizable. The number of video screens and the size of each screen can be modified based on needs.
Figure 4.5 Tree view: the list of segments (nodes)

Note. The node numbers are assigned in order of their creation, which does not necessarily reflect their time sequence. In the list above, Node 1 and 2 are created first, and then Node 1 is divided into Node 1, 3, and 4.
Figure 4.6 ITMD research system analysis interface

Note. The ITMD analysis interface is designed for use with two computer monitors so that the researcher can watch and code the video at the same time.
EPILOGUE
Why Rethinking Cognitive Tool?

The term, “cognitive tool” is widely used in more conceptual senses in other field of knowledge, such as one’s mind, symbols, language or knowledge as a cognitive tool. In Instructional Technology, the tool becomes a tangible object that learners use for their learning. Rethinking of cognitive tool, therefore, was a necessary effort of finding the meaning of cognitive tools for the design, development, research and practice beyond its abstract conception. The first paper, *Reframing Research on Learning with Technology: In Search of the Meaning of Cognitive Tools*, provided a conceptual framework for research and development of cognitive tools. The two studies, *Creating a Universe with Computer: Charting the Structure of Distribution between Learner and a Cognitive Tool* and *The Evolution of the Intellectual Partnership with a Cognitive Tool in Inquiry-Based Astronomy Laboratory: Icebreaking, Getting Along, and Bonding*, were the actual investigations of the structured conceptions: what intellectual partnership between learners and the tool is actually looks like (i.e., what features are used or not used and how they are used for certain cognitive tasks); and how learners’ growing expertise in use of the tool for scientific inquiry impacted their development of intellectual partnership with the tool and how those partnerships evolve over time. The last paper, *Looking through Multiple Lenses: Reflection on the Methodological Approach in Learner-Technology-Activity Interactions* formally presented the methodology with which cognitive tools can be studied in our field.

These articles are targeted for researchers and designers whose works are focused on the formative research and development of interactive learning technologies as well as the practitioners who attempt to adopt innovative learning technologies and approaches in classrooms. Hopefully, the ideas and approaches in this series of papers could advance the way we view, design, develop, apply and study computers in education so that we can provide more valuable learning experience to learners and helpful information to other researchers and practitioners in the field.
APPENDIX A

PRE-COURSE SURVEY
Please answer the following questions on this paper:

1. Semester and year in which ASTR1010 is taken: _________________________

2. What other courses or experiences have you had that might have enriched your Astronomical understanding (e.g., high school experience, summer camps, etc.)?

3. Have you ever taken a lab course that uses computer before? Yes No
   If yes, please briefly describe how you used computer in the course:

4. Please list the purposes for which you generally use computers at home or other sites:

5. Have you ever taken a lab course with open-ended inquiries? Yes No
   If yes, please briefly describe what it was like:

6. Have you done some group-work in other classes? Yes No
   If yes, please briefly describe what it was like:

7. Please provide a general comment on your confidence, concerning your previous lab experiences, in performing the lab assignments without difficulties:

8. Were you aware of what you would do for this lab (computer modeling, reports, etc.)? Yes No
   If yes, please describe what you know about this course; if no, please describe what you had expected:

9. Please provide a general comment regarding your interest in this subject and how you came to take this course:
APPENDIX B

THINK-ALOUD PRACTICE
Think-aloud Practice

As part of the research project, we are interested in what you are thinking about when you do your lab activities. The technique we use is called “think-aloud.” It is pretty easy. The idea is that when you are doing a lab activity you say out loud what you are thinking. For example, if you were scrambling eggs you might say the following as you were doing making the eggs:

First I grab the cast-iron fry pan because it seems to cook a lot of eggs faster than the other pans. Then I crack the eggs on the side of the pan so that I just crack the shell, but not so I crush the whole egg. There is one, just right. Oops, I cracked that one too hard and now I got broken shells in the egg. I grab them with my finger by pushing it on the bottom of the pan and sliding them up the side of the pan. Now once I have all the eggs in, I break the egg yokes with a fork and scramble them lightly. I don’t like to beat them with a blender because it makes too many dishes to clean up.

The following task is a short exercise to help you practice thinking out loud as you work.

Work out the following problem on the back of this paper. Remember to talk out loud so that you can be heard by a person sitting right next to you; but not so loud that you can be heard across the room. Make sure you talk about everything that you are thinking about whether you think it is important or not.

Here is your task:

1. Read the following problem and try to interpret it (all this process in your head should be spoken aloud):

   You have created a planet (Rasoon) and a star (Cistaur). The planet Rasoon rotates on its axis once every 2.5 Earth days and revolves around the star once every 750 Earth days. Assuming that a year in Rasoon is one revolution around Cistaur, how many Rasoon days does the Rasoon year have?

2. Use the top/back of this paper to jot down notes or pictures to solve the problem on this paper (all this process in your head should be spoken aloud).

3. Use the bottom/back of this paper to write down the answer and your justification (all this process in your head should be spoken aloud).
APPENDIX C

POST-COURSE SURVEY
Please answer the following questions on this paper:
Your Name:

1. What did you like most about this lab? Describe any experiences that led to excitement, achievement, or ah-ha moments, etc.

2. What did you like least about this lab? Describe any experiences that diminished your learning or caused you confusion, frustration, etc.

3. How helpful was your Astronomy course (ASTR1010) for your success in this lab? Please explain.

4. How helpful was this lab for your understanding of astronomy? Please explain.

5. Comment on using Astronomicon in the lab:
   a. How well did you understand about models and their associated theories?
   b. How confident were you in using it?

6. What is your favorite feature and why?
   c. What are your concerns about it?
   d. Other comments:

7. How would you characterize your and your partner’s contribution to the group work? Please describe your role vs. your partner’s role, percentages of workload, etc.

8. What was your experience in writing the lab report? (e.g., ease or difficulty in understanding the exercises, in deciding on which screen captures to use, in deciding how to articulate your findings, etc.)

9. How helpful was doing presentations for your understanding of astronomy concepts? Please explain.

10. How helpful was listening to the presentations of other groups for your understanding of astronomy concepts? Please explain.

11. Did you have enough guidance and support from the instructor and your peers? Please explain.

12. How would you describe your interest in Astronomy at this time? Please explain.

13. We would like to contact you to schedule an interview to ask further questions. During the interview, you will have a chance to see some video clips we recorded during the lab. Please provide your contact information below and circle your first preference for communication. Email: ________________ Telephone: __________________
APPENDIX D

SAMPLE FIELD OBSERVATION NOTE ABOUT GROUPS
Questions & next week presentations are assigned to groups (presentation group in bold). Chris has assigned the same question to groups 3 and 6 because I have expressed my interest in comparing those two groups.

3) Do lunar phases depend on where on the Earth you are? - *Group 1*
4) Is there a relationship between the Moon’s rotation and revolution? - *Group 9*
5) What does the Earth look like from the Moon? - *Group 3 and Group 6*
6) What do superior planets look like from the Earth? - *Group 4 and Group 7*
7) What do inferior planets look like from the Earth? - *Group 5 and Group 8*

Chris' interaction with participants: The instructor's interactions with groups seem to be different depending on where they sit in addition to how they ask for help from him. Prominently, I have observed some differences for the following three groups

Group 1: When Chris provides guidance for extended time to this group, he drags the empty chair by Allen (where group 2 used to sit). Today, he asked them to draw a diagram of Sun-Earth-Moon system on a paper to help them understand the relationships and then sat by Allen to explain further about the perspectives.

Group 4: Chris interacts more with this group because of their calls for help. There are white boards around the room, but I have seen Chris using the board that Group 4 is facing several times to give them mini-lectures. He also often bestrides on the instructor desk while talking with them. Today, he was instructing them to draw a diagram on a paper, sitting on the desk.

Group 5: Today, Chris was using the right corner of the white board in the front in order to explain the orbital relationship among Sun, Earth, and Venus.

With the groups in the places where he does not have any access to the dependable objects, he often stoops down behind the two group members to talk.

Other things happened...
With Mindy: At the Beginning of the class, Chris came to me, handed me with Mindy's exercise 3 report,
and told me that she would bring her exercise 2 report next week. When she was leaving after finishing her lab, she told me that she read my email in the morning and was not able to bring it with her.

With Dan: His computer mouse was missing today. I looked for any available extra mouse in the closet, but none was there. He finally asked me if there was any extra after trying to work without it for a while. I took out one from Chris's computer and gave it to him. Later, the technician told me that the mouse had been stolen.

With Mark: Mark seems to be very friendly and sociable. He always nods his head lightly or smiles to people who have any eye contact with him. Today, his group finished very early. Joe just left without being bothered by this, but he waited behind Chris for some time while he was talking with group 4, as if he wanted to tell him that they were leaving. However, he left without talking to him because Chris' involvement for the guidance was taking little bit longer and he did not notice Mark.

With Betty and Allen: Allen asked Chris about any available copier because he wanted make a copy of Betty's notes. I offered to make a copy for them and asked Betty if I could make a copy for myself as well. She was fine with it.
APPENDIX E

DOCUMENT COLLECTION NOTE AND LINKS TO THE FILES
Collection of Documents

Week 1 (08/25/03): Lab Introduction

- Course Syllabus

Week 3 (09/08/03): Software Introduction

- No handout was distributed

Week 4-5 (09/15/03 & 09/22/03): Basic Solar System Observation

- Sample Report
- Exercise 1

Week 6-7 (09/29/03 & 10/06/03): Time

- Exercise 2
- Exercise 1 reports with grades (two people have not submitted)

Week 8-9 (10/13/03 & 10/20/03): Orbits

- Exercise 3
- Change: 2-a) The orbital speeds and periods of planets decrease as you go outward from the Sun
  --> The orbital speeds of planets decrease and their periods increase as you go outward from the Sun
  (This one was supposed to be the correct hypothesis, but actually was incorrect)
- Exercise 2 reports are graded, but unable to make copies this week (10/20/03).

Week 10-11 (10/27/03 & 11/03/03): Phases

- Exercise 4

A body texture that the instructor made and brought to the class: This is made in order to make
the third model of #2.

- Graded exercise 2. One of them is missing (Mindy). A copy is requested to the participant.
- Exercise 1 reports that were not submitted by absentees are requested to the instructor. One of
  them never submitted the first report.
- Photo copy of Mindy's exercise 3 report: Rest of the graded & commented electronic copies of
  exercise 3 reports will be collected next week.
- Photo copy of Betty's notes on exercise 4
Week 12-13 (11/10/03 & 11/17/03): Eclipses

- **Exercise 5**
  - Change: 9-b) If you were on the Moon you would see the Earth eclipsed by the Moon
    --> b) If you were on the Moon you would see the Earth eclipsed by the Sun
- Graded exercise 3
- Kim's exercise 1 report
- Photo copy of Mindy's exercise 2
- Photo copy of Betty's notes on exercise 2, 3, & 5

Week 14-15 (11/24/03 & 12/01/03): Seasons

- **Exercise 6**
  - Change: B. 3-b) The seasons are caused by the Earth changing speed in its orbit. [*That is the earth spends a longer time closer to the sun during the summer than in winter.*] --> [disregard this sentence]
  - Graded exercise 4
APPENDIX F

SAMPLE EMAIL CORRESPONDENCES WITH THE INSTRUCTOR
Hi, Chris.

I have a quick question about building the model. I saw you helping group 1 with planets moving opposite direction. Allen mentioned that you could do with minus rotation rate, and you led them to think for inclination. What is the underlying conceptual reason for using inclination over minus rotation rate?

Beaumie.

Beaumie again...

I looked at the edit window and realized that you cannot make the orbital periods with minus value even with the circular orbits. In the real world, if you have an orbit with nearly 180 inclination, do you always get a minus orbital period so that it will still move in the same direction?

Beaumie.

I think that using the inclination to make the planet move in the opposite direction is just the way to do it in the program. In reality we can't really see the difference between a 0 or 180 inclination. Also I think the only
way a planet would move in the opposite direction of all the others is if it was captured by the sun and did not form around it. Hope this helps.

Chris

------------------------------------------------------------
From: Beaumie Kim
Sent: Wednesday, October 22, 2003 11:01 AM
To: Chris Anderson
Subject: RE: A Question about 4-a

Thank you, Chris!
It does help. In fact, when you make a waypoint from the sun looking at the Earth with 180 degrees inclination, the Earth is not upside down even though it is moving in the opposite direction. (with 179 degrees, it is upside down).

Why would all the planets move in the same direction? Does that mean that all planets in one system move in the same direction whether it is counterclockwise or clockwise?

Thank you very much for your help!
Beaumie.

------------------------------------------------------------
From: Chris Anderson
Sent: Wednesday, October 22, 2003 2:26 PM
To: Beaumie Kim
Subject: RE: A Question about 4-a

No problem. They would all move in the same direction from the theory of how the solar system is formed. Essentially a cloud of gas combined and rotates into a center bulge (eventually the sun) and a disk (where the planets are formed). As a result of the rotation of the disk, all the natural planets of the system should rotate the same way. I don't know if there is a specific rule for clockwise or counterclockwise when comparing solar systems, but ours could be either depending on how you look at it.

Chris
APPENDIX G

A SAMPLE EXERCISE WORKSHEET
Exercise 4

The Moon and Phases

The purpose of this section is to investigate the appearance and cause for phases of the Earth, Moon and planets. Be especially careful of where your viewpoint is.

1) From memory, write a definition of phase as it applies to astronomical bodies such as the moon.

2) What causes lunar phases?
   a) Phases of the Moon are caused by a shadow from the Earth
   b) Lunar phase are caused by the changing position of the Moon with respect to the Sun
   c) Lunar phases are caused by its own light changing

The instructor will assign you one or more of the following sets of theories.

3) Do lunar phases depend on where on the Earth you are?
   a) Different countries see different phases of the Moon on the same day
   b) Everyone on the Earth sees the same phase of the moon

4) Is there a relationship between the Moon’s rotation and revolution?
   a) The Moon only shows one face because it is rotating once every time it revolves around the Earth.
   b) The Moon only shows one face to us because it is not rotating.

5) What does the Earth look like from the Moon?
   a) If you were on the Moon, the Earth would not have any phases.
   b) If you are on the Moon, the Earth undergoes phases just as the Moon does.

6) What do superior planets look like from the Earth?
   a) Superior planets do not have any phase change.
   b) Superior planets undergo a full set of phases (new, quarter, full)
   c) Superior planets undergo only a limited set of phases

7) What do inferior planets look like from the Earth?
   a) Inferior planets do not have any phase change.
   b) Inferior planets undergo a full set of phases (new, quarter, full)
   c) Inferior planets undergo only a limited set of phases

Now you have decided which one is the real and which is not, discuss why would make those alternative theories (some of them had once been accepted as true by scientists) by comparing between the observations from the correct model and those from the incorrect.
APPENDIX H

A SAMPLE ANALYSIS TABLE I
<table>
<thead>
<tr>
<th>Activity: ex.4-#2- a/b comparison</th>
<th>Instructor</th>
<th>Knowledge</th>
<th>Function</th>
<th>Representation</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Phases of the moon are caused by a shadow from the earth b) Lunar phases are caused by the changing position of the Moon with respect to the Sun</td>
<td>KK to class:  - Overall goal is to look at the phases  KK to group:  - Comparing phases. Support part b over a</td>
<td>Definition of phases  - AC of Betty: by the shadow from the earth (from her note, and the pretest)  - Allen: phases by the moon orbiting the earth, and its location</td>
<td>MBI-2: examination of the question  - supposed to compare the way different phases look (Betty)  MBI-4: making claims (Betty, N23)  - difference in fuzziness between half moons of the two models (fitting into the suggestion)  - “full moons and new moons are gonna be same”  Seeking help from the instructor:  - seeing the difference b/w phases of two model</td>
<td>Representation of knowledge  - Conversations  - Notes: drawing in her note comparing the shapes</td>
<td>Knowledge that affects distributed relationships  - Rules:  o Relationships among different parameters (e.g, mass, diameter, rotation rate, tilt)  o Configuration of the space (the distance and direction)  o Others (temperature, etc. that we put as new features)</td>
</tr>
<tr>
<td>a) Epicycles b) Software basic modeling</td>
<td>FK to class:  - look at the moon from the earth after building  FK to group:  - Waypoint: Very rarely stay above same point  All offsets to zero</td>
<td>Functional knowledge:  - About the tool (computer general, Astronomicon, or other tools such as calculator)  - Process knowledge (MBI, other ways to reason)  MBI-3: Modeling and Validating (Betty)</td>
<td>MBI-3: Modeling and Validating (Allen)  - opens the model A (N25), running it, zooms in  - opens the model B</td>
<td>Representation of function  - Conversations  - Thinking aloud</td>
<td>Functions that are utilized by users  - Observational methods  - waypoints  - zooming  - ambient light setting  - Timer acceleration and deceleration  - Timer reverse motion  - Timer day counts, resets Visualized  - Orbital disks  - Blue selection box, locating bodies</td>
</tr>
<tr>
<td></td>
<td>a) Shadow casting; The Moon looking from the Earth b) Basic light from the star; The Moon looking from the Earth</td>
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<tr>
<td><strong>RK to group:</strong></td>
<td><strong>MBI-4: observing</strong></td>
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<tr>
<td>- true difference comes into play in-between half and full or in-between half and new (N24)</td>
<td>- looking at the way different phases look: full moon A vs. full moon B; half moon A vs. half moon B (N23)</td>
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<tr>
<td>- go in-between to get a good picture</td>
<td>- half moons are what we need to look, or supposed to see the difference</td>
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<td><strong>KR to group:</strong></td>
<td><strong>MBI-5: Collecting pix</strong></td>
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<tr>
<td>- rounded donut analogy (gibbous phases with bite out) (N24)</td>
<td>- May need to get closer and take closer pictures of half moons (Betty, N23)</td>
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<td>- take out all the pictures of half moon (Betty, N25)</td>
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<td></td>
<td><strong>Function of bringing or deciding on representations</strong></td>
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<td><strong>MBI-4: observing and looking for the proofs</strong></td>
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<td>- half moons: real one is more fuzzy and a) is more straight on (Betty, N23)</td>
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<td>- opening the folders with pictures, opening the picture of the half moon of each model</td>
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<td>- Allen cannot tell the difference b/w the two (N23)</td>
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<td>- In one of the model, the phases are not as rounded (Betty, N24)</td>
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<td></td>
<td>- Model A, Moon from the Earth</td>
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<td></td>
<td>- Recognizing the different patterns of crescent moon</td>
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<td><strong>MBI-5: Collecting pix</strong></td>
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<td></td>
<td>- Deleting all the pix of half moons (N25)</td>
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<td></td>
<td>- Taking pix of both waning and waxing crescent moons, Model A, then Model B</td>
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<td></td>
<td><strong>Representations to share with others</strong></td>
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<td></td>
<td><strong>Observed</strong></td>
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<td>- Moon from the Earth, Model A, showing the Earth shadow passing (N24)</td>
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<td>- Moon from the Earth, showing phases</td>
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</tbody>
</table>

Note. The number following letter “N” indicates the node number.
APPENDIX I

A SAMPLE ANALYSIS TABLE II
<table>
<thead>
<tr>
<th>Knowledge Structure</th>
<th>Astronomicon</th>
<th>Inquiry</th>
<th>Team Building</th>
<th>Pattern Recognition</th>
<th>Pattern Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>29-Sep</td>
<td>def. day/month/year</td>
<td>Betty not much developed skills of controlling the software Waypoint: staying on the surface, horizon as a tool (Sunrise)</td>
<td>Betty starting note-taking</td>
<td>N1, N2. Betty's attempt for modeling and observing</td>
<td>N4. Betty suggesting to see from above</td>
</tr>
<tr>
<td>Timing Day</td>
<td>N4. Mass-Gravity-Orbital rate (velocity = mass X acceleration)</td>
<td>N3. Data collection (repetitive process)</td>
<td>N2. Giving up by not getting the expected result, moving back to Allen's</td>
<td>N5. Betty realizing the problem of .5 day while observing</td>
<td></td>
</tr>
<tr>
<td>N9. New Moon is dark</td>
<td>N8. Diameter &amp; day length, not well-explored</td>
<td>N9. Making predictions (when they will see the change day15 - 45)</td>
<td>N9. Making predictions (when they will see the change day15 - 45)</td>
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<td>6-Oct</td>
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<tr>
<td><strong>Timing Month</strong></td>
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<tr>
<td>N5. Circular orbits vs. mass-distance effects (Referring to the crazy planet made last wk)</td>
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<tr>
<td>N6. Moon mass and the length of the month</td>
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</tbody>
</table>

| Circular orbits |
| Lab Report needing sufficient supporting data; overall conclusions |
| N3, N5. Trying another way to time a month |
| N5. Not investigating why the two timing yield different results |
| N6. Allen being carried away by noticing something |
| N6. Trying what they did w/ day: diameter, mass and month |
| Report: incomplete in talking about three theories and comparing them |

| Betty late by 50 minutes |
| N3. Repeating what they already did last week w/o Betty |
| N6. Betty getting the activity and observation focused: Telling Allen what needs to be done |

| Comparing w/ same viewpoints; data for process and results (no need repetition) |
| N3, N5. Timing a month: moon around the Earth (phases/revolution) |
| N6. Ways of representing observations (showing how big it is with shadow) |

**Note.** The number following letter “N” indicates the node number.
APPENDIX J

A SAMPLE RECALL INTERVIEW PROTOCOL
Greetings:
- Life, classes, major(s), year in college, future plans, etc.

Warm-up Info & Q:
- Format of the interview:
  1. Discussion about the clip (1st class on phases)
  2. Astronomicon model
  3. Some general questions
- As you think about your experiences in this class, what events or experiences stand out for you? Tell me about the times that were most interesting, least interesting, and most frustrating during the lab.

What happened that day:
- Instructor’s explanation of how to approach the first problem
- 1st attempt: trying to distinguish models A & B with the days it took to go through a full set of phases
- 2nd attempt: comparing new/half/full/ with shadow and with light and dark phases
- 3rd attempt: comparing and recapturing crescent and gibbous moons

<table>
<thead>
<tr>
<th>Clips &amp; Models</th>
<th>Questions</th>
</tr>
</thead>
</table>
| Clip 1: confused, not understanding what is going on No… but cause it’s just me (node 15) (episode1-1) taking pictures of shadowed phases (have the exercise ready) | Very active thinker!  
What were you thinking b/f and a/f his talk?  
How did you come to understand?  
What were the difficulties? |
| Clip 2: Trying to fit the observation into the supposed-to-be (node 23)(1-2) (after the instructor suggests comparing what phases look like for each model) | attempt to make two different theories to fit into the category…  
How were you making connections among what you saw on screen, what you already knew, what you heard from the Instructor? |
| Clip 3: Oh, I see it! (node 25) (1-3) (after the instructor suggests about the phases to compare, donut example) | What was your expectation b/f watching it?  
What took you to understand what is going on? |
| Clip 4: “There are so much you could do with this program” (node 11) (episode2-1) (after instructor suggests finding the right radius for the moon) | Things you were thinking of based on what you see, and hear…?  
What would you change if you can change your experience with the lab? |
| Model 1: Full Earth from the Moon (Switch to the Earth to Moon view) | What can you tell me about the status of this model? (relationship among them, what would Moon look like from the Earth, etc.) |
| Model 2: Waxing Crescent Moon from the Earth (Switch back to the Moon to Earth view) | Same  
Why Earth is not in exact waning gibbous phase? How would you investigate that? |

No clip
- What were the most frustrating features to use? (not bugs)  
- Any moments: only if Astronomicon could do this….  
- Changes in your thinking about Astronomy, Science, what you see in life, any inquiries?
APPENDIX K

BEHIND THE STORY: RESEARCHER, PARTICIPANTS, AND VIDEO
Researchers as Learners

Researchers in the context are active learners who construct meanings with learners, about the learners and about their learning (Kelly & Lesh, 2000). Researchers in some sense engage in very similar kinds of thinking processes to those of learners. Resembling learners’ scientific thinking for inquiry, their reasoning comes between their continuous observations, constantly testing and connecting with their theories and making inferences based on them (Dewey, 1910/1997).

Learning about/from Various Aspects

In addition to observing how the designed activities are carried out as a class, the inferences are made about the groups such as the relationships between pairs and their roles within a group, the instructor’s relationships with learners. The understandings about the groups and their interactions provide important foundations (having the big picture) for the close observations through the video and become main tools for group selections. Researchers also collect documents to learn from various sources. For the two studies, the researcher participated and collected various documents in the class for the entire semester for fifteen weeks.

The documents created by participants are the supplementary data for qualitative research because they are often collected to support and expand what we see and hear through other sources (Glesne, 1999; Merriam, 1998). Especially for the research on the complex interactions of joint learning systems, the learners’ reflective reports cannot be used as the main source. The kinds of document data for the current research, however, make important contributions to the researcher’s understanding about what happens in the classroom, as they are integral parts of the entire picture. Documents such as course syllabus and exercise sheets with questions for each topic provide information about the designed structure of the course, which paint the front-end of the picture and guide observations in the context as well as through the video. The students’ written reports then become the other end of the picture, which conclude their inquiry activities for each exercise. These reports actually reveal some of their thought processes of making conclusions and how they use the software to come to the conclusions.
Learning about Astronomy and Astronomicon

Artifacts created by the participants or the researcher are often collected as research data (Merriam, 1998). In this astronomy lab, learners always interact with the models they create with Astronomicon for their scientific inquiry. These models therefore are important learner-created artifacts that are integral to their learning process. For the purpose of the research studies, the models were not collected from the learners, but reconstructed by the researcher whenever necessary. Examining models are important to gain deeper understandings of their learning processes by interacting with specific features of Astronomicon. As researchers of advanced learning technologies, we are often involved in subject-matters that we are not specialized in. Therefore, we need to be actively engaged in the learning activities in the classroom as researchers and learners. The occasional interactions with the instructor during the research period included not only the understanding about the learners’ progress through the instructor’s point of view but also the questions and answers regarding modeling and understanding astronomical phenomena using Astronomicon after the class period or through emails (see Appendix C).

Context, Video, and Reality

There are many different analysis techniques for video data depending on the purpose of the study, as for text data. Video data can be analyzed to quantify findings for ergonomics of human-computer interaction by scoring with predefined taxonomy of behavior (e.g., (Laws & Barber, 1989). In TIMSS and TIMSS-R video research, video data were collected as survey materials (Stigler, Gallimore, & Hiebert, 2000). In some other occasions, video is used as an ethnographic method (e.g., (Goldman-Segall, 1998). Video-based approach emphasizing on capturing every participant of the learning activity puts the researchers into an interesting place when working with the video: they are no longer in the context yet feel as if closer to the experiences of the learners. Researchers deal with multiple versions of the same learning event (reality) throughout the research process, and presumably in the case of video-based research, another version is added to the research cycle (see Figure 5.1). The learning designs propose a reality that occurs in the future, the actual class brings the designs into the reality, and the video shares the reality some of which could not be perceived by the eyes of researchers. We interpret and
represent each version of the reality to make connections among them and finally construct our own being translated by our theoretical lenses (Riessman, 1993).

Figure 5.1 The multiple version of reality in research

The reality in the video for this research maintains the richness that is close to the original context, and yet adding more complexity by providing access to the every moment and detail of interactions. When the researcher starts watching the video, she starts to participate in the cognitive activities of learners, thinking with them in their problem solving situations. Betty and Allen, partners of one of the groups are engaged in thinking of changing the length of a day and they have changed the diameter of the Moon. The researcher hears their conversations, observes their interactions with Astromicon and other resources, and participates in the activities of the joint learning system, which was not possible to do in the actual context.

The experience in the classroom then helps situating herself in the context by zooming in and out of the event. Consider this scenario of watching a short segment:

1. [Betty and Allen (Group 1) are observing their model. Marcy’s (in Group 8) voice is in the background, saying something to the instructor. The instructor then starts responding to her.]

2. Allen: Is she complaining? ’Cause she needs to stop talking!

In this segment of observing the group with Betty and Allen, the researcher can only hear the voice tones of Marcy and the instructor in the background. Without listening to the conversation between Marcy and the instructor, the researcher can recall the event from the day of observation and decide not to examine further, but to grin at Allen’s reaction and move on. The conversation between Marcy and the instructor was about the same lab course that uses a different structure of curriculum:

3. [The instructor is about to leave Group 8 after helping them with their modeling.]
4. Marcy: [turning back to the instructor] Oh, my friend is taking this lab that starts in the afternoon, and she told me theirs lab is harder than ours.

5. Instructor: Well, it is different. It is not necessarily harder.

In many cases, learners’ decision-makings are influenced by their listening to some hints or responses to other groups’ questions provided by the instructor. On these occasions, the researcher is drawn back to the context of the classroom and provides her own insights for understanding the salutations.

Video Cameras and Participants in a Digital Complex

Conscious or not, the presence of video camera changes the interactions of participants, or creates new ones. At the same time, it changes the relationship of the researcher with participants. The important thing to consider is whether those changes are relevant to our research questions (Roschelle, 2000). With the current research agenda, the learners’ reactions to the video cameras were not directly relevant to their interactions with the software, but at times reflected how they relate to the cameras.

The participants in this class are situated in a digital complex, where they are surrounded by the cameras, the computers, and the digital audio recorder with headsets. Some learners build very interesting relationships with the cameras that the researcher (who is completely outside of that complex) can never have. Betty first finds out about the minimized window that displays the video encoding process on her computer. It was when Allen insisted on sorting out some problem without asking the instructor that Betty opens the window:

6. [Betty sighs, looks at the camera, and turns toward her computer. She opens the video encoding window and watches it.]

7. Allen: [looking at Betty’s screen] Oh, we can watch ourselves? That’s so wrong!

8. [Betty giggles.]

9. Allen: [taking his palm out and covering his face] Don’t look at my face! (Figure 5.2)
Starting from this day, Betty opens that window off and on between their times of engagements in the activities, waving to see the time lapse among real time and two displayed ones, and sometimes just to watch herself like a mirror (her hair).

Out of this digital complex, the researcher only builds the broad insights on how different groups work and how the instructor gives guidance to the learners. The observational focus in the classroom naturally follows the movement of the instructor as where he goes is the places where problems are solved and interesting conversations become audible by learners’ turning toward the instructor.

The world that the researcher knew from the classroom with entire group, on the other hand, becomes completely different when watching videos. In the world of video, the two partners in a group are captured in a view, becoming the center of the world, as opposed to their being one of the groups guided by the instructor. The world around them now appears to be the environment in the background outside of their small digital complex that only gives some influences at times.

References


