Design-Based Research - More than Formative Assessment?
An Historic Account of the Virtual Solar System Project

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Introduction

Over the past eight years, we have engaged in a series of related projects to develop the educational potential of the emerging technology of virtual reality. We have tackled the many dimensions of this challenge through a set of design-based methods that have iteratively evolved these projects, our theories, and our methodologies. This article describes the evolution of a particular hardware/software technology developed for use within an intro-level astronomy classroom, but, more than that, it also chronicles the dramatic shifts in thinking related to pedagogical and curriculum structures developed over the course of the study. We argue that this design-based research goes beyond successive iterations of formative evaluation to improve a particular instructional product, in that it focuses on the development of more broadly applicable theories, models and insights vital in the development of emerging technologies for learning.

This study begins with an overview of the original vision of the project and the specific educational needs it was addressing. After contextualizing the overall approach, we present three distinct phases of the project and highlight the evolution of its key dimensions: Educational Technology, Pedagogical Theory, and Curriculum Theory.

The Virtual Solar System Project Vision

> ...One group of students narrowed their investigation to ants. Unlike the hundreds of Ms. Perez-Drake's students over the years who simply drew pictures to memorize ant anatomy, these students used an animation simulator. With this tool, the students created a three-dimensional moving ant model. When they forgot to include all the limbs, their creation hobbled jerkily. This humorously reinforced basic facts about movement and structure...
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> (CEO Forum School Technology and Readiness Report, June 2000)

Although the Virtual Solar System Project (VSS) was well underway by the time the CEO Forum's provocative image was published in 2000, this anecdote publicly captured our vision of the project and validated our agenda to create new forms of VR educational software. Here students were quickly building rich, dynamic, isomorphic models of the phenomenon they were studying instead of simply drawing static representations, relying on preconstructed virtual simulations as surrogates for reality, or attempting to overcome the learning curves of the scientist's abstract formalisms.

Generally models provide powerful ways to represent understanding; they can be exploited by scientists and learners alike. Our approach to virtual modeling joins an emerging body of research developing and studying modeling technologies and pedagogies in science education (Jackson, Stratford, Krajcik, & Soloway, 1994, Linn, diSessa, Pea, & Songer, 1994, Penner, Lehrer, & Schauble, 1998, White & Frederiksen, 1998, etc.). Such research has produced two prominent approaches to modeling: simulation and model building.

On the one hand, simulations approaches to modeling feature pre-developed models that serve as surrogates for the real world. The *SimCity* series is a popular example; *ThinkerTools* (White & Frederiksen, 1998) is another that has been rigorously studied. Using models, students conduct systematic inquiry much as they would in the real world. The advantages of simulation-based inquiry over real-world inquiry are that everyday pragmatics of time, distance, safety and the like can be overcome as students focus on collecting rich data sets for their inquiry.

On the other hand, both the CEO modeling activities and our approach are consistent with the second prominent approach to modeling – model building. A rich history of research supports the advantages of student model-building approaches (Feurzeig, 1988; Roberts & Barclay, 1988; Roth, 1992, Tinker, 1993 & Ogborn, 2000). In model building, students construct their own models either through physical means (i.e. Penner, Lehrer, & Schauble, 1998), model-building toolkits (i.e. Jackson et. al., 1994), or meta-modeling languages (i.e. Resnick, 1996). The act of model building allows students to engage in a design process (Jackson et. al, 1994; Lehrer, Horvath, & Schauble, 1994), which begins with a set of tentatively accepted theories that evolve into coherent understandings as represented in their models (Roth, 1996; Sabelli, 1994). Research on model building argues that students are forced to "make explicit their own conceptions of a phenomena" (Confrey & Doerr, 1994), validate their resultant model, and iterate the process to develop increasingly richer conceptions.

In keeping with this framework, we have developed powerful modeling-based pedagogies and tools for learner creation of isomorphic 3-D models and visualizations in weather (Hay, 1999), astronomy (Hay, 1999; Hay & Barab, in review), and animal behavior (Hay, Crozier, & Barnett, 2000). These pedagogies and tools combine to create powerful learning environments that promote significant learning in the deep structure of a domain (Barab, et.al., 1998). To illustrate our approach, this paper focuses on design-based research we conducted on a virtual modeling tool, Astronomicon, that supports an astronomical understanding of planetary motion and light.

Need

During the past decade, numerous studies [116 since 1988 according to Pfundt & Duit's (1998) bibliography] have reported difficulties in student understanding of basic astronomical phenomena (Wandersee, Mintzes, & Novak, 1990). Such difficulties were highlighted in the film, *A Private Universe* (Schneps & Sadler, 1988), where 21 of 23 Harvard graduates described incorrect conceptions about the cause of the seasons.

The need for astronomy tools whereby students can more easily overcome their misconceptions and conceptual shortcomings in part drives our forays into VR modeling research in astronomy. The Virtual Solar System Project enables students to effectively build VR models of the objects of study (i.e., planets) with contemporary computers. In doing so, the project addresses the well-documented need in university astronomy courses to improve students' conceptual understanding of light, motion, and force.

Emergent Learning Environments and Design-based Research

Our research agenda focuses on a precise subset of emergent learning environments relevant to education at the intersection of three dimensions of instruction. We focus on emerging VR technologies with unique learning features that have "face validity" for promoting and supporting learning. While these learning features can address economic and practical concerns (i.e. make learning more cost efficient or easier to deliver), our primary interest is in learning features that are related to pedagogical concerns (i.e. creating new opportunities for insight). Specifically, we have focused on research and development of constructivist/socio-historical learning environments that identify, analyze, and develop unique features of emergent technology to meet both traditional and emergent learning objectives. These types of learning environments bring together a dizzy array of variables, issues, and challenges.

Design-based research, as articulated by Brown (1992), introduced a research approach that focuses on the messiness of experimentation in naturalistic settings by systematically varying aspects of each new iteration of an intervention. This approach is ideal for our work in developing emergent learning environments because it provides a way to more rigorously investigate the opportunities that an emergent technology might create for learning and instruction.

This investigation might be characterized as a straightforward formative evaluation of an instructional product, a criticism leveled again design-based research. However, Barab and Squire (2004) assert that one of the major differences between design-based research and formative evaluation is "the fact that design-based research may generate new theories (not simply testing existing theories)."

In the realm of emergent technology development, the theoretical potential of design-based research is an important contribution. The use of design-based research approaches to explore the potential of new technology features often creates a domino effect of insights that are not simply progressive enhancements of the initial instructional vision. The results are often dramatic shifts in thinking and insight that can extend contemporary theories of learning, pedagogy, and curriculum.

Research **Context**

Although our approach to design-based research[1] employed many innovative features, we were committed to maintaining the basic instructional objectives as defined by the community of astronomy educators, the textbooks available for this course, and the collaborating faculty. Our goal was to enrich and connect these objectives, rather than to change them. Our research and our iterative development were seen in the context of this complexity.

Several considerations grounded our approach. First, because we were committed to conducting research and development in an authentic learning environment in a naturalistic setting, we chose to study an intro-level astronomy classroom designed for non-major university freshmen. Second, the project collaborated with senior university astronomy faculty to design the courses, technology, and instructional materials. Third, instead of viewing the students as "subjects," we viewed them as participants throughout all phases of the project. As participants in the research, the students added insight into the ongoing program of research and development. Fourth, the project eschewed simplistic attempts to isolate single variables to test. Instead, we looked at multiple variables through constructing scientific modeling approaches, new educational VR software, instructional modeling activities, and new assessment techniques.

Primary Research Methods

In a task-structured curriculum, such as the Virtual Solar System Project, researcher most often study these environments by videotaping learners in the process of building knowledge.

[1] To describe differences between design-based research and other methodologies in our description of the Virtual Solar System Project context, we use the categories developed by Collins (1999). His categories include Location of Research, Complexity of Variables, Focus of Research, Unfolding of Procedures, Amount of Social Interactions, Characterizing the Findings, and Role of Participants.

However, researchers who study such processes in these settings often have been forced to limit their focus to whole-group processes, a single individual or small group of students, or activity snapshots. Occasionally, they forego classroom research entirely and resort to laboratory settings.

To understand and characterize the intersection of new technology, learning objectives, and pedagogies, we developed a methodology called the Constructing Networks of Action-Relevant Episodes (CN-ARE) method (Barab, Hay, & Yamagata-Lynch, 2002). CN-ARE methodology involves tracking the emergence, evolution, and diffusion of concepts in activity systems. It is based on the actor-network approach (Latour, 1987; Roth, 1996), a sociological approach that involves selecting a tracer (e.g., conceptions and alternative conceptions of light and planetary motion) (Newman, Griffin, & Cole, 1989; Roth & Roychoudhury, 1993) and following its history through a node/link activity network representing the historical development of each concept.

CN-ARE integrates a network approach for capturing the distributed and situated nature of knowledge-in-the-making, enabling in situ study of learning in naturalistic classroom settings. Networks are constituted by collections of *nodes* (chunks of activity) and *links* (thematic connections among the nodes), which when combined into a web illustrate the relationships among the nodes (Degenne & Forse, 1999; Schvaneveldt, 1990).

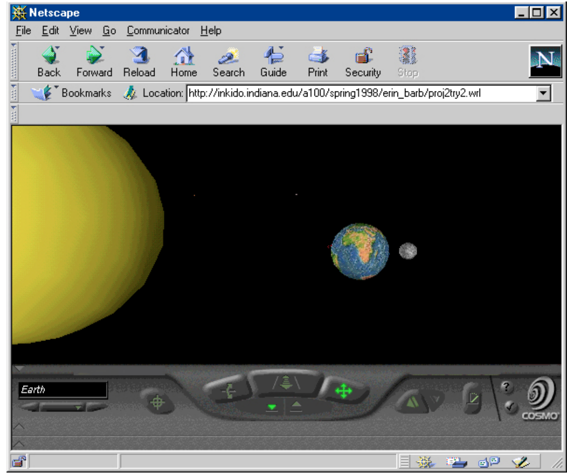
In the final phase of the project, CN-ARE was augmented with standardized pretest and posttest knowledge measures that were used to provide sufficient statistical and interpretive power for measuring learning gains. We used selected items on light and planetary motion from three previously developed and validated tests: Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992), Project STAR-Astronomy Concept Inventory (Sadler, 1998), and the Astronomy Diagnostics Test (Zeilik, Schau, & Mattern; 1998). These tests were developed to not only assess whether learners think as astronomers, but also to assess the presence of common alternative misconceptions.

Project Phases

The project evolved in three discernible phases: Phase 1-Initial Conceptualization, Phase 2-New Pedagogy and Technology, and Phase 3-New Curriculum. In what follows, we characterize these phases and present in order of importance the three major components of R&D work involved in each (Modeling Technology, Pedagogical Theory, and Curriculum). We conclude each phase with a set of summary findings and insights. Further, we keep in mind that the presentation of these phases as discrete is a rhetorical device to facilitate analysis and does not fully capture the complexity of the research. There were many sub-phases, and phases blended together in multiple and nuanced ways inasmuch as they were distinct. Our goal is to use these phases to highlight the dramatic shifts in our thinking that went beyond formative evaluation at each phase, and furthermore to present the domino effect of this dramatic shift to our current thinking.

Phase 1-Initial Conceptualization

The initial conceptualization of the Virtual Solar System (VSS) was similar to Ms. Perez' ant software: Students would construct virtual isomorphic models, models that looked liked the thing that they were modeling, to understand the phenomenon. This approach had been previously tested and studied (Hay and Barab, 2002) within a summer program with middle



school students. These modeling activities included the construction of the interior of a planet, the construction of the Earth, Moon, and Sun system, and finally the construction of the entire Solar System with planets and major moons. Phase 1 incorporated the core VR model-building idea into the rigors of an academic course

Modeling Technology – General Purpose VR Construction Kit

The Phase 1 VR technology was a commercially available direct manipulation VRML construction tool running on a high-end workstation (Silicon-Graphics). VRML is the VR standard for the web, and it enabled ready access to VR modeling without the need for learning programming. All motion was created by frame-based animation techniques. For example, to create a rotating Earth students created a sphere, sized the sphere based on their scale of the model, textured the sphere with a mercator project map image so that it looked like the Earth (see Figure 1), then rotated the sphere at several "keyframes" in the animation. Students then put these keyframes on a time line and finally scaled the timeline to represent 24 hours. The resulting animation featured the Earth rotating on its axis in a 24-hour period.

Figure 1. Mercator Projection Map of the Earth and Textured Sphere

Pedagogical Theory – Constructionism

The Phase 1 pedagogical theory was based on Papert's notion of constructionism, a. theoretical framework that comes out of research and development of the Logo programming language (Papert, 1980). Constructionism builds on constructivism in that it distinguishes itself from more traditional instruction, in part, by its assumptions about learners' ability to create meaning, understanding, and knowledge. Rather than viewing students as passive receptacles of teacher-imparted knowledge, Papert argued that not only can knowledge be built by the learner, but that these processes occur most "felicitously" when learners are engaged in the construction of an artifact or shareable product.

Our basic pedagogical approach in this research incorporates constructionism to build on the earlier work of Winn (1997), who had students develop their own virtual world. We had students build their own models of planetary dynamics using CosmoWorlds. For a more detailed description and implementation of constructionism in the Virtual Solar System Project see Hay and Barab (2002).

Curriculum – Construction of the Solar System

The Phase 1 curriculum was comprised of a set of distinct construction activities: Construct an Earth, Moon, and Sun system; construct a model of the interior of a planet; and construct the entire solar system. These activities were ordered through a "conceptual coherence" model. As typified in conventional curricular models and rooted in classical associationist models of learning, this curriculum starts with easier questions and modeling tasks and progresses to more difficult ones. Students worked in collaborative teams to construct the models correctly, and the models represented assessment artifacts. Faculty focused on evaluating the quality of the models.

Findings and Insights

Our research documented important learning gains (Barab, etc. 2001) and concluded that this approach was generally accepted by the students and professors. However, there were a number of important issues that needed to be addressed.

First, the constructionism framework did not anticipate an obvious question posed by students: "How good should my model be?" Because the model was not built for any authentic purpose other than a graded assignment, this question was a deceptively important one that was not handled well by the astronomy faculty.

Second, without a direct purpose for the model building, students were not focused on learning that was embedded in their model. While students constructed models that reflected phases of the moon, they often focused more intently on completing a model than on understanding the nuances about lunar phases represented in their model. Students did not learn these concepts as deeply as we had hoped.

Third, a number of important issues arose with the technology. The CosmoWorld only ran on high-end graphic workstations (~$15K) and not on readily available educational computers. The tools of key-frame animations created a somewhat high initial learning curve, as well as an artificial representation of planetary motion that was not in line with how scientists think about planetary motion. Moreover, the technology was unforgiving to bad initial assumptions. If a student did not set up planets and viewpoints correctly, most often they had to throw out their initial models and restart from scratch. Finally the technology did not enable students to dynamically manipulate basic parameters like time[2].

Phase 2- New Pedagogy and Technology

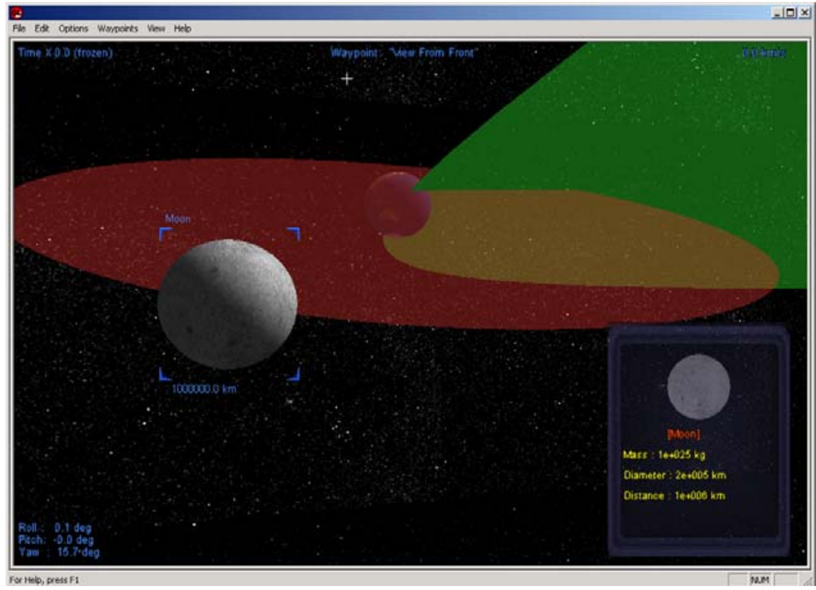
Phase 2 saw significant changes to the Virtual Solar System Project based on the findings of Phase 1. This phase instituted dramatic changes to the modeling technology, pedagogical theory, and research technology.

Modeling Technology – Astronomicon Version #1

With a small university grant, we were able to develop a prototype astronomical modeling tool we called Astronomicon. Astronomicon overcame many of the issues identified in Phase 1

[2] The timescales of the solar system are vast (i.e., a solar eclipse happens in minutes, yet it takes ~250 years for Pluto to orbit the Sun).

critiques of CosmoWorld. It ran on Windows machines with high-end graphics cards, enabled planetary motion defined in astronomical terms and interfaces, allowed students to easily manipulate time and distance, and incorporated easy-to-use features for students to employ in initially developing and modifying their models.



Pedagogical Theory – Modeling-Based Inquiry

The pedagogical innovation of this phase builds on a specific pedagogical strategy, Modeling-based Inquiry (see Table 1), using Astronomicon to support the process. Modeling-based Inquiry focuses on scientific methodologies involving phenomena that are difficult or impossible for scientists to study empirically. Scientists use computational models not as representations of the final product, but rather as both a source of data and a support for their conclusions. Modeling-based Inquiry put the student in the position of a scientist as they built their own computational models and drew data from them.

1. Begin with an inquiry question.
2. Plan the model & collect data.
3. Create a 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.
8. Present conclusion to colleagues.

TABLE 1

The Modeling-based Inquiry approach combines the instructional benefits of inquiry-based and constructionist approaches. This approach stands in contrast to typical modeling pedagogies that rely on teachers constraining the unattainable goal of "realism" and that focus on specific knowledge (i.e., phases of the moon). In the data collection phase of inquiry projects, students use their model as a surrogate for the real phenomena. However, unlike simulation-based inquiry pedagogies, students themselves build the model and either understand its inner workings or engage in the process of understanding them. Students can therefore warrant their tentative conclusions using explicit assumptions reflected in their model. This model of pedagogy was developed based on discussions with collaborating computational scientists on this new way of doing computational science (Sabelli, 1994).

Curricular Theory – Conceptual Coherence

We continued with a conceptual coherence model of the curriculum of Phase 1. However, in addition to building increasingly difficult models, the curriculum was developed in terms of a set of inquiry questions (i.e., What causes the phases of the Moon?). The progression of inquiries started with the most accessible concepts and the easiest model to construct and became increasingly difficult as the students went along.

Findings and Insights

The Modeling-based Inquiry approach provided students clear focus that drove them to investigate and explore the curriculum objective, as defined by the astronomy community, in a precise manner. This outcome was evident in students' discussions and written assignments. However, in interviews students still maintained profound misconceptions that emerged when they were pushed to explain certain astronomy concepts in depth. For example, students spent an entire semester looking at planets and moons that were half illuminated. However, when pushed on their explanation of phases of the Moon, learners often reverted back to explanations that included the Earth's shadow causing phases.

Phase 3-New Curriculum

The Phase 3 iteration of the project was primarily driven by a change of curriculum, which in turn drove refinements of both technology and activities.

Curricular Theory – Building Misconceptions

The new thinking about the VSS curriculum attempted to focus on orchestrating the curriculum to directly address misconceptions. We developed two curricula: Historical Recapitulation and Alternative Theories. The Historical Recapitulation (HR) curriculum was based on Wandersee's (1986) suggestion that learners benefit from addressing scientific domains by recapitulating the path through which scientific concepts are initially formulated. The Alternative Theory (AT) curriculum was focused directly on misconceptions identified in the literature. The Conceptual Coherence curriculum was supplemented through the direct introduction of theories and models that were based on misconceptions.

Pedagogical Theory – Modeling-Based Inquiry

In the HR condition, activities focused students' attention on the historical backstory of an inquiry activity. Students built models consistent with the historically accepted theories, and then used these models and known data of the time to find the "crack in the theory." They would then "fix" the theory with a historically acceptable solution. Each inquiry activity formed the theory/model for the next inquiry activity. Students finished the course with currently accepted models of planetary motion and light.

In the AT curriculum, students were instructed to judge competing theories. Students were given an inquiry question and two to four theories that addressed the question. For each inquiry question, one of the theories was the currently accepted theory, while the others were based on misconceptions identified in the educational literature. Students built models for each of the theories and used them to prove which theory was correct and why the others were incorrect.

Technology – Astronomicon Version #2

In order to support the curriculum and the pedagogy, Astronomicon needed to support modeling incorrect models. This requirement was a significant challenge for the design team: how to make doing something wrong easy to do. For the HR curriculum, tools were needed to support both currently accepted and previously accepted (but incorrect) astronomy models. For example, Astronomicon had to support modeling an Earth-centered vs. Sun-centered solar system, circular orbits vs. elliptical orbits vs. off-set orbits, and orbital equation-based orbits vs. physics-based orbits (vectors for forces and velocity). For the AT curriculum, Astronomicon needed to support completely wrong models based on misconceptions. This requirement was challenging because misconceptions often do not completely hold together; students often leave out significant elements in their model.

Findings and Insights

We are currently still engaged in Phase 3 data analysis; however, we can report some interesting findings. Overall, the HR curriculum was not well received by students. Our current thinking is that because most students had significant background knowledge in the area, historic notions of the solar system did not make sense to them. They could not suspend their knowledge and pretend to believe that the Earth was the center of the solar system. At times this issue led to students simply walking through an exercise to get it done instead of intellectually engaging the inquiry. On the other hand, the AT curriculum worked well overall. Students were forced to directly confront and prove that a theory was wrong, and to prove why the currently accepted model was correct. We saw significant learning gains in students who engaged in this inquiry activity.

The improved technological features in Astronomicon that enabled students to build and compare both accepted "correct" models and "incorrect" models based on misconceptions and rejected historical theories were largely effective for improving understanding of astronomy concepts. We are engaged currently in analysis of the types of activities that "worked" to improve this understanding.

Toward this end, one of the most powerful approaches we have developed in the research methodology is to develop models of students that improved between pre- and post-tests. We have conducted a thorough investigation of these types of students through the CN-ARE approach to understand how they overcame misconceptions of phases (Hay, et al, 2004). We will further this research with CN-ARE to understand how students that did not overcome their misconceptions compared in this model. We believe this general approach will lead to valuable insights.

Reflections on Design-based Research

The goal of this paper was to give an historic account of the dramatic shifts in our thinking as we conducted design-based research of virtual reality technology to meet the needs of astronomy students. These shifts occurred through intensive research throughout all levels of this project – educational technology, pedagogy, and curriculum. We believe that one of the keys of design-based research is the integration of research insights derived from an iteration with other newly found theories and ideas, as well as with the insights of all the participants. Together, these elements are negotiated through the constraints of the targeted naturalistic setting.

In the context of developing emerging educational technology, such integration does not mean the incremental improvement of the original instructional product. Rather, it means the commitment and the courage to use these insights to design future iterations that incorporate dramatic shifts in thinking. Such shifts in thinking are a necessary aspect of the design-based research approach, both advancing the quality of innovations and contributing to the field more generally.

References

Barab, S. A., & Squire, K. (2004). Design-Based Research: Putting a Stake in the Ground. *Journal of The Learning Sciences, 13(1),* 1–14.

Barab, S. A., Hay, K. E., Barnett, M. G., & Squire, K. (2001). Constructing virtual worlds: Tracing the historical development of learner practices/understandings. *Cognition and Instruction, 19(1),* 47–94.

Barab, S. A., Hay, K. E., Squire, K., Barnett, M., Schmidt, R., Karrigan, K., Yamagata-Lynch, L., & Johnson, C. (2000). Virtual solar system project: Learning through a technology-rich, inquiry-based, participatory learning environment. *Journal of Science Education and Technology, 9(1),* 7-25.

Barab, S. A., Hay, K. E., Yamagata-Lynch, L. C. (2001). Constructing networks of activity: An in-situ research methodology. *Journal of The Learning Sciences, 10(1&2),* 63–112.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. Journal of the Learning Sciences, 2(2), 141-178.

CEO Forum (June 2000) School Technology and Readiness Report.

Collins, A. (1999). The changing infrastructure of education research. In E. C. Lagemann, & L. S. Shulman (Eds.) *Issues in education research: Problems and possibilities*. (pp. 289–298). San Francisco: Jossey-Bass Publishers.

Confrey, J. & Doerr, H. M. (1994). Student modelers. Interactive Learning Environments 4(3), 199-217.

Degenne, A., & Forse, M. (1999). Introducing social networks. Thousand Oaks, CA: Sage.

Feurzeig, W. (1988). Apprentice tools: Students as practitioners. In R.S. Nickerson & P.P Zodhiates (Eds.), Technology in education: Looking toward 2020. Hillsdale, NJ: Erlbaum.

Hay, K. E. (1999b, April). The Digital Weather Station: A Study of Learning with 5D Visualization. Manuscript presented at the annual meeting of the American Educational Research Association, Montreal, Canada

Hay, K. E., & Barab, S. A. (2001). Constructivism in practice: A comparison and contrast between apprenticeship and constructionist learning environments. *Journal of the Learning Sciences, 10(3),* 281–322.

Hay, K. E., Kim, B., & Couch-Roy, T. (2004, April). Virtual Reality Modeling-based Inquiry: Conceptual Coherence and Alternative Theories Trials. Manuscript presented at the annual meeting of the American Educational Research Association, San Diego CA.

Hay, K.E, Crozier, J., & Barnett, M. (2000). The Virtual Gorilla Project. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Jackson, S. L., Stratford, S. J., Krajcik, J., & Soloway, E. (1994). Making Dynamic Modeling Accessible to Precollege Science Students. Interactive Learning Environments, 4(3), 233-257.

Latour, B. (1987). Science in action: How to follow scientists and engineers through society. Milton Keynes, England: Open University Press.

Lehrer, R., Horvath, J., & Schauble, L. (1994). Developing model-based reasoning. Interactive Learning Environments, 4(3), 219-231.

Linn, M. C., diSessa, A., Pea, R., & Songer, N. B. (1994). Can research on science learning and instruction inform standards for science education? Journal of Science Education and Technology, 3, 7-15.

Newman, D., Griffin, P. & Cole, M. (1989). The construction zone. New York: Cambridge University Press.
Ogborn, J. (2000). Modeling clay for thinking and learning. In W. Feurzeig & N. Roberts (Eds.) Modeling and Simulation in Science and Mathematics Education.(pp. 5-37). NY: Springer-Verlag.
Papert, S. (1980). *Mindstorms: Children, Computers, and Powerful Ideas*. NY: Basic Books.
Penner, D. E., Lehrer, R., & Schauble, L. (1998). From Physical Models to Biomechanics: A Design-Based Modeling Approach. Journal of the Learning Sciences, 7(3&4), 429-449.
Pfundt, H., & Duit, R. (1998). Students' Alternative Frameworks and Science Education. Bibliography. 5th ed. Kiel Univ. (West Germany). Institut fuer die Paedagogik der Naturwissenschaften.
Resnick, M. (1996). New paradigms for computing, new paradigms for thinking. *Constructionism in Practice: Designing, thinking and learning in a digital world*. Y. Kafai and M. Resnick. Mahwah, NJ, Lawerence Erlbaum Assoc.: 255-267.
Roberts, N., & Barclay, T. (1988). Teaching model building to high schools students: Theory and reality. Journal of Computers in Mathematics and Science Teaching, Fall, 13-24.
Roth, W. M. (1992). Bridging the gap between school and real life: Toward an integration of science, mathematics and technology in the context of authentic practice. School Science and Mathematics, 92(6), 307-317.
Roth, W.-M. (1996). Knowledge diffusion in a grade 4-5 classroom during a unit of civil engineering: An analysis of a classroom community in terms of its changing resources and practices. Cognition and Instruction, 14, 170-220.
Roth, W.-M. (1996). Knowledge diffusion in a grade 4-5 classroom during a unit of civil engineering: An analysis of a classroom community in terms of its changing resources and practices. Cognition and Instruction, 14, 170-220.
Roth, W.-M., & Roychoudhury, A. (1993). The concept map as a tool for the collaborative construction of knowledge: A microanalysis of high school physics students. Journal of Research in Science Teaching, 30, 503-534.
Sabelli, N. (1994) On using technology for understanding science. Interactive Learning Environments 4(3), 195-198.
Schneps, M. H.& Sadler, P. M. (1988). A private universe. Santa Monica, CA: Pyramid Films
Schvaneveldt, R. (Ed.) (1990). *Pathfinder Associative Networks: Studies in Knowledge Organization*. Norwood, NJ: Ablex.
Tinker, R. (1993) Modeling and theory building: Technology in support of student theorizing. In D. L. Gerguson (Eds.) Advanced educational technologies for mathematics and science. Berlin: Springer-Verlag.
Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1990).Research on alternative conceptions in science. In D. L. Gabel (Ed.), Handbook on Science Teaching and Learning (pp. 177-210). New York: Macmillan Publishing Co.
Wandersee, J.H. (1986). Can the history of science help educators anticipate students misconceptions? Journal of Research in Science Teaching, 23(7), 581-597.
White, B. Y. & Frederiksen, J. R. (1998). Inquiry, Modeling and metacognition: Making science accessible to all learners. Cognition and Instruction, 16(1), 3-118.
Windschitl, M. & Winn, B. (2000). A virtual environment designed to help students understand science. Proceedings of the International Conference of the Learning Sciences. Ann Arbor, MI, 290-296.

Hestenes, D., Wells, M., & Swackhammer, G. (1992). Force Concept Inventory. The Physics Teacher, 30(3), 141-158.
Sadler, P. M. (1998). Psychometric Models of Student Conceptions in Science: Reconciling Qualitative Studies and Distractor-Driven Assessment Instruments. Journal of Research in Science Teaching, 35(3), 265-296.
Zeilik, M., Schau, C., & Mattern, N. (1998). Misconceptions and their change in University-Level Astronomy Courses. The Physics Teacher, 36(2), 104-108.