Learner-Centered Design for Effective Education Software

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ABSTRACT

There is a growing realization in education than didactic, lecture-based modes of instruction are less effective than more learner-centered models in which learners, frequently in collaboration with peers, are engaged in problem solving and inquiry. Predicated on constructivist and situated notions of what it means to know and learn, many educators are suggesting the creation of learning environments that support the natural complexity of content, avoid over-simplification, engage students in knowledge construction, and present instruction in real-world contexts. Rather than presenting instructional treatments, the goal is to establish rich learning environments where learners engage in domain-related practices to carry out socially negotiated tasks. In this paper, the authors argue that a new model based on designing tools for learners, not just users, is needed. Learner-centered design focuses on creating an interface that is easy to use and facilitates the development of domain understanding. This approach can overcome the learner's lack of domain knowledge and skills so that a novice can accomplish meaningful tasks within a relatively short period of time. Application of learner-centered design in the domain of a satellite orbital control simulation system is discussed.

ABOUT THE AUTHORS

Ken Hay is a Research Scientist in the Learning and Performance Support Laboratory and Assistant Professor in the Instructional Technology department of the College of Education, The University of Georgia. In the LPSL, Dr. Hay spearheads the lab's core R&D effort to develop and understand emerging technologies and learning. Dr. Hay received his doctorate in Instructional Design and Technology from Ohio State University. Academic credentials also include post-doctorate work in the Advanced Technologies Laboratory and the Highly Interactive Computing Environments Research Group at the University of Michigan. Dr. Hay has taught in the third grade, middle school math and science, technical college, and in the university for over 12 years. His primary research interest is the development of a Learner Centered Design Model that guides designers in the development of tools for learners, where the tools become a means to support learners in complex, authentic activity. Using a constructivist/situated cognition framework, he is also interested in the more global research that looks at the emergence, evolution, and diffusion of knowledge within technology rich environments.

Charles J. Cohen has been working in the fields of image processing, robotics, human-computer interaction, and artificial intelligence for over a decade. At Cybernet, he has been the project manager for many projects for the United States Armed Forces (Air Force, Navy, and Army), National Aeronautics and Space Administration, and other government agencies. His projects include work on simulation, training, real-time optical pose determination, robotics, virtual reality, object identification, feature and body tracking, and human performance evaluation. Dr. Cohen's main areas of interest is gesture recognition and massive number of agent network architectures and systems, which he is developing and integrating for the Army and Air Force.

Ron Hay is a lead developer in Cybernet's Virtual Reality group, specializing in graphics programming (using both OpenGL and DirectX). The core technology for the Virtual Reality group is the OpenSkies Simulation System. OpenSkies has been through several iterations of development over the past four years, and includes a complete, standalone HLA implementation of great sophistication, standalone components for panel development, physics simulation, scenegraph API, scenario development and deployment, and collision detection. It has been used for everything from a first-year Naval pilot trainer, to a massive-multiplayer game, to an astronomy education tool. Mr. Hay has acted as one of the primary developers for the system since its birth.

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INTRODUCTION

In this paper we present a set of core networked, virtual reality-based model building technologies that will form the foundation for a wide range of educational applications. The central innovation is to give students powerful virtual reality (VR) modeling tools to explore fundamental questions of science by independently or collaboratively constructing VR models of scientific phenomena, sharing and co-habiting these virtual models with other local and remote students, mentors or teachers through the web, and presenting these models to large on-line audiences, all within an inquiry framework. In our work we have separately demonstrated the core technological capability in both the development and testing of VR model building toolkits and networked-based VR interactions.

Previous learning research has shown that core VR model building technology can effectively be designed in a way that promotes educational outcomes. This work has shown that constructing VR models for inquiry leads to a vastly deeper, interconnected, and engaged understanding of the domain, the development of inquiry and problem solving skills, and that, with proper initial instruction, students can engage this type of instruction at a distance. This proof of concept has included the design and development of the VR technology, instructional methods, other instructional resources, evaluation methods, and other educational “models of practice.” Innovative technology cannot just be thrown at educators; but it must be designed and supported in a holistic fashion that integrates incites from scientists, practitioners, educational theorists, and technology developers. Only with this type of commitment will educational technology maximize it full learning potential. These results also support the National Research Council’s (NRC) National Science Education Standards' (1996) specific recommendation that students should be "involved in some way in scientific inquiry, not just a hands-on experience." We believe that this instructional approach and technology will open up an entirely new mode of instruction that will be extendable to many mathematics, science, and technology domains.

BACKGROUND

Distance Education has largely been stuck in the technological reproduction of past methods of instruction. HTML has spawned what are essentially electronic textbooks, while video conferencing has spawned networked lectures. These new versions have advantages over their predecessors (i.e. HTML-based books have multimedia elements and are instantaneously updated, and videoconferences can reach a broader audience on demand). We would argue that these technological enhancements are similar to what happened when film first came on to the scene. Early filmmakers placed cameras in the best seat of a theater and filmed the stage actors' play. The argument was, "everyone has the best seat in the house" and the play would have "much larger audiences." It wasn't until the film industry developed new techniques and special effects that the medium matured to what it is today, an entertainment experience that is vastly different than a play.

We argue that developers of distance education are following the same path in the information age. That is, they are fundamentally stuck in traditional patterns of thinking; they are not thinking "out of the box." We argue that the real educational opportunities and the highest gain will not come from reproducing enhanced traditional instruction. It will come from the development of new modes of learning and new models that can take advantage of the unique features of new technology to promote the primary goals of education: deep understanding and problem solving skills to the broadest audience possible. This paper illustrates the development of a technology-enhanced instructional method that does precisely that; provides a new instructional method that will promote deeper understanding of standards-based content, be more broadly accessible, and address problem-solving skills that are vital in the information age.

The Learning Framework

The learning research in cognitive science has demonstrated that students learn in deep and enduring ways when they are actively engaged in authentic, relevant problems. Our work is based on two major foci that are blended together: investigation-based learning and constructionism.

We are distinguishing learners doing scientific investigations (Blumenfeld et al., 1991; Ruopp et al., 1993; Tinker, 1993) from learners receiving science instruction. Instruction includes the performance of exercises or activities designed to illustrate a single science concept. Although an investigation might include a series of activities or exercises designed to help children learn concepts or processes relevant to solving a problem, it is decidedly more than this. An investigation is a comprehensive perspective focused on actively engaging learners in authentic scientific inquiry. As learners pose questions, investigate, and seek resolutions to those questions, they acquire a deeper understanding of scientific principles and concepts.

The second component of our theoretical framework builds on the work of Papert (1991) at the MIT Media Laboratory. His notion of constructionism builds on constructivism in that it distinguishes itself from more traditional instruction, in part, by the degree of active learner engagement, as well as the assumption that learners have the ability to create meaning and knowledge. Papert (1991) argues that not only can knowledge be built by the learner, but that these processes occur most fluidly when learners are engaged in the construction of an artifact or shareable product. Thus, constructionism (e.g., the construction of a virtual solar system) allows learners to test out their emergent conceptions of phenomena in a manner that will demonstrate the flaws in their thinking.

Our Approach: Virtual Modeling Building

We have developed a space-based virtual-reality construction software tool we call the Astronomicon. This software is a virtual 3-D modeling environment where learners can construct their own virtual models of the solar systems. These projects will be situated within inquiry-based experiences. That is, students will build the virtual models within the context of answering questions about the solar system. Thus the goal is not to build a model of the solar system, but rather to build a model that will help you answer the question, "How many eclipses are possible in a year?" or "What would happen to the seasons if the earth had a 45 degree tilt?" These questions will require learners to use DoED, NSF, and NASA data and web resources, both in creating their models and in exploring design parameters. In this environment, learners will construct models through our direct manipulation interface, will be able to explore fundamental science concepts in a more exhaustive manner, and will be able to collaboratively interact with other learners throughout the world via the Internet. This software represents an exciting learning environment to use the power of cyberspace to learn about outer space.

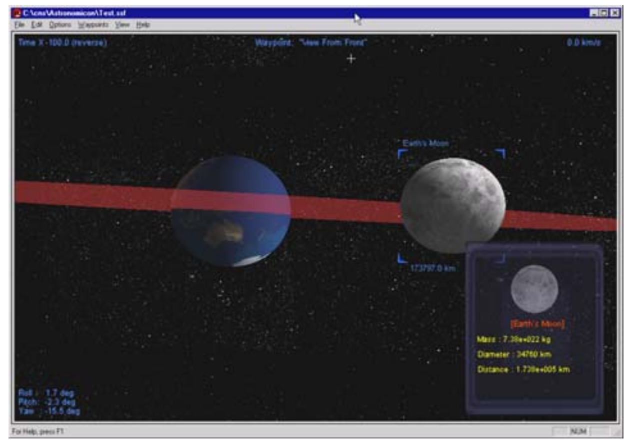

Figure 1. Screenshot of Astronomicon

VIRTUAL MODELING-BASED INQUIRY OF THE SOLAR SYSTEM

Learners use our software to create a virtual model of the solar system to understand foundational questions of planetary motion. The key point is that learners are not exploring someone else's model, but rather they plan their model, collect basic facts of their model, enact those into the model, and explore relationships through their model. We have found that through this process learners must enact abstract facts into dynamic models. Even simple facts like the 23^0 tilt of the Earth, engages them in deeper ways that traditional instruction. This simple fact masks the underlying complexity of what it means. The students must negotiate 23^0 from what? In what direction? Does it change as it rotates? As it revolves? Enacting this fact pushes students to understand the plane of the ecliptic, as well as form foundation understanding of seasons and the precession. These opportunities grow and increase as they build models and engage in inquiry, and, as they take advantage of these opportunities, they build rich understandings of the dynamics of the solar system (Barab, Hay, Barnett, & Squire, 1998).

As a way of an example, let's turn to Tim and Tami, hypothetical students, as they use our software to confront a challenge when their model does not behave like it should.

Scenario

Tim and Tami enter the software at remote locations. Their goal is to address the question: When, where and how eclipses occur? They interact via a 2-way audio interface and plan out what facts they need to build their model. Then they find the sizes, orbital periods, etc. of the Earth, Moon, and Sun from web resources. Within 30 minutes, they have constructed a realistic virtual model of the Earth, Moon, and Sun system. Now the question is when does an eclipse occur? After exploring their dynamic model they see that they don't know how to "see an eclipse" from outer space. To see an eclipse they have to be on the earth, they hypothesize. They move to the Earth and look out towards their virtual sun. They quickly notice an eclipse, and then another one, and another. One of the student's comments that eclipses are occurring too often in their model, one per month. Tami asks, "What's going on?" Tim says, "This is not right, there must be a problem with our model." Showing their model to an online mentor or peer, they determine that they forgot to include the Moon's orbital tilt. They correct their model and see that eclipses are now occurring much lest frequently.

They work with the model, visualizing the plane of the ecliptic and moon's orbital plane to help them address the main question. They conclude the lesson by creating an audio walking virtual tour of their world and their explanation of when, where and how eclipses occur. This tour is posted up on the web and can be seen by peers, teachers, parents, and relatives.

EDUCATIONAL STANDARDS, GOALS AND OBJECTIVES

A major component of *every* middle grade's earth science curriculum, and one of the NRC (1996) standards related to Earth Sciences, is that students develop an appreciation of "Earth in the Solar System." However, due to the lack of computational mathematics skills, understanding of this topic necessarily remains at a descriptive level not noticeably beyond that typically achieved in the elementary grades. For example, many students will not go beyond understanding that the Earth is the third planet from the Sun in a system that includes the Moon, the Sun, eight other planets and their moons, and smaller objects, such as asteroids and comets.

The modeling possible with the virtual environment we are proposing, which is quantitative in its underlying operation, can help students to move beyond the purely descriptive to an understanding of the relationships between relevant variables, particularly when explicitly related to earlier learning in a physical science context: A central aspect of NRC Earth Science standard related to the Earth in the Solar System is that students develop an appreciation that most objects in the solar system are in regular and predictable motion. Those motions explain such phenomena as the day, the year, phases of the moon, and eclipses. Gravity is the force that keeps planets in orbit around the sun and governs the rest of the motion in the solar system.

Central to having a qualitative understanding of "regular and predictable motion" is having a quantitative appreciation for these dynamics. Our previous research has suggested that the power of learners creating and exploring virtual models of the solar system is that they enact quantitative data into photorealistic objects that personalize the data and create opportunities for them to understand the quantitative nature of the solar system (Barab, Hay, Barnett, & Squire, 1998). Virtual reality is an environment that is uniquely suited for the dynamic nature of planetary motion. This research has shown that students do not effectively blend the lectures, 2D static images, and textual descriptions of planetary motion. Building virtual reality models is the right match for the content and builds deep understanding of the 3D nature of planetary motion and the inquiry skills of model-based science.

MODULES

Our approach is that students are not exploring someone else's model, but rather they plan their model, collect basic facts for their model, enact those into the model, and explore relationships through their model, all to address driving questions. We have found that through this process, students build rich understandings of the dynamics of the solar system. Furthermore, well-crafted driving questions help push learners to deeper understanding of the science. Our consultants have developed a set of driving questions, which they are currently using with off-the-shelf software, that focus on planetary motion in five general topic areas.

Heliocentric Versus Geocentric Views

This includes celestial sphere, precession, sidereal/synodic periods, apparent retrograde motion, and retrograde orbits.

Planetary Rotations and Tilt

This includes day/night, changing day lengths, equinoxes and solstices, planetary illuminations, phases, planetary tilts, direct/indirect sunlight, and seasons.

Eclipses

This includes eclipse seasons and line of nodes.

Kepler's Laws

This includes 3-D orbital parameters (eccentricity, inclination, etc.) and geosynchronous orbits.

Newton's Laws

This includes gravity, center of mass, and escape velocity.

BEHAVIORS

Isomorphic modeling (showing objects exactly as they are) provides powerful mechanisms for model builders. However, the power and the goal of analogies and models lay in understanding the underlying "systematic relational structure" of what we refer to as the *behavioral model.* This aspect of the model defines attributes that enable the Earth to orbit the sun. They move learners developmentally from dependence on literal surface features to understanding analogies and models involving deeper, often underlying functional features. Put simply, deeper understanding evolves as the focus shifts from isomorphic to behavioral models.

Move from Isomorphic Models to Behavioral Models

The significance of isomorphic models is underscored by widely reported problems associated with students "getting stuck" or continuing to rely exclusively on surface features. For example, sustained focus on surface features interfered with students' conceptual understanding of physics problems (Chi, Feltovich, & Glaser, 1981, Larkin, 1983; Larkin et al., 1980). While we concur that many learners initially need to build models with surface features that approximate the real world (isomorphic models), they must move beyond surface features for complex learning to occur. However, this is a challenge for novice modelers. Returning to the students with Styrofoam ball elbow, their focus on surface features created a conceptual dead-end that stymied further inquiry. Students needed to discard the previous model and start anew with different materials better suited to modeling functional features.

The flexible integration of our isomorphic and behavioral modeling environments precludes conceptual dead-ends by allowing learners to quickly create isomorphic models and transition to deeper issues. In our early work with the VSS Project, students would first put a photorealistic texture onto generic white spheres to represent each planet's surface appearance. However, later they found that white textures with latitude lines (a simply implemented change) were more valuable than the realistic textures for their inquiry into the seasons (Hay & Barab, 2001). This confirms Lehrer and Schauble's (2000) observation that as students gain skill and understanding, "the properties of resemblance that initially sustain them fall away." Representational systems are usually grounded in resemblance between the model and the world, but these representations typically "undergo fundamental transformations via inscriptions" (Lehrer & Schauble, 2000).

Learners must evolve from their isomorphic models to models that reflect "higher-order relations" to guide ongoing inquiry. It is critical to differentiate the affordances of isomorphic modeling in model building from those in a simulation learning environment. In a model building environment, the isomorphic properties create linkage between the real world and the model, keeping learners from becoming mired in a disconnected world of code or concept maps. Isomorphic modeling bridges reality and the underlying relationships represented in the model. In contrast, simulations emphasize "high fidelity" representations deemed fundamental to learning; an error in realism may lead learners to draw incorrect conclusions. In modeling environments, feature omission is acceptable and even expected, provided the features are not central to the current inquiry. "The focus is not on whether a particular model is right or wrong but the degree to which it is able to account for the phenomena as currently construed" (Penner, Lehrer, & Schauble, 1998). In modeling environments such as ours, greater importance should be placed on *stimulating* rather than *simulating* (Resnick, 2000).

The Cascade of Behavioral Models

The transformation of surface features into something useful to inquiry is the first necessary step but it is not sufficient in the evolution of models. Students should be involved in what Hestenes (1992) called the "modeling games" evident in the practices of scientists. These have variously been called "cascades of inscription" (Latour, 1987), "families of models" (Penner, et. al, 1997), and "a multiplicity of epistemic forms and games" (Collins & Ferguson, 1993). In an ideal cascade, the learner's activity should flow naturally from the surface features to the underlying behavioral model that represents the relational structures of the model.

In our work we have refined and tested different approaches to facilitate this transformation. Specifically, we pursued theoretical and technological insights that guide learners through the transformation from isomorphic to behavioral representations of scientific phenomena.

The first step was to identify model elements that are unseen (i.e. forces in *Interactive Physics*) or unseeable (i.e. molecules in *ScienceSpace*). Unseen or unseeable elements are important, not only because they represent much of the most interesting science, but also because they are difficult for learners and are linked to a wide range of scientific misconceptions (Pfundt & Duit, 1998). The key is that unseen or unseeable elements are grounded within isomorphic models - forces are applied to the molecules to make up "real" objects. The power of computational modeling is that these unseen or unseeable elements become reified (Winn, 1999) within the virtual environment, making them "visible" and subject to inquiry. Thus they become accessible and usable in students' models and influential in testing and refining their understanding.

In our Virtual Solar System project, for example, learners visualize the orbital planes of the Earth and Moon – key elements in deepening their understanding of eclipses. In our Virtual Exploratorium project, learners used powerful 3D visualization tools to observe previously unseeable elements such as airflow in a global convection cell of the Walker Cell and the local convection cell of a thunderstorm cell.

The second transformation priority was ensuring that isomorphic models evolved smoothly as increasingly complex models, understanding, and inquiry are developed. Lehrer and Schauble (2000) discuss increasing complexity in cognitive terms: *representational systems, syntactic models*, and *hypothetical-deductive models*. Conversely, Hestenes (1996) characterizes increasing complexity in structural terms: *systemic, geometric, temporal*, and *interaction*.

In our work with students building 3D solar system models, one particular case exemplifies this transformation. The student's goal was to create a moon orbiting the earth. The software environment was a general purpose VRML modeling software designed for content developers. In his initial explorations, the student created an Earth and moon of an arbitrary size on a portion of the screen and found that he could grab the entire space as if it were a clear glass cube containing the Earth and moon. Almost accidentally, he found that, with quick click, drag, and release manipulations, he could grab and release the cube and the objects would continue to move — to spin. The moment of inspiration was palpable and readily discerned. Because the cube was spinning at its center, the student began the quest to identify the center and place the earth at the center. He then asked the professor to demonstrate how to model the moon orbiting the earth. This started an important conversation around the strengths and weaknesses of the model. The experience started the student on the "cascades of inscriptions," or better yet the cascades of models, to a model that was considerably more mathematical. The learning environment must support a wide range of different types of underlying model building tool kits, starting with direct manipulations.

A third step in transformation was the exploration of rival models. It took thousands of years to move from a geocentric view of the solar system to a heliocentric one. In real world inquiry, this type of conceptual leap is difficult for learners — even when presented strong evidence contradicting the initial model (Chinn & Brewer, 1993). It is also problematic in modeling environments. Children generally struggle to generate competing models of a phenomenon (Grosslight, Unger, Jay, & Smith, 1991).

The modeling environment we created enabled learners to easily create rival models in the same space. Whereas Penner, Leher, and Schauble's (1998) learners initially constructed non-isomorphic physical models using different "modeling materials," our modeling environment supports a multiplicity of modeling "epistemic forms and games" enabling "ruptures in understanding". Such ruptures required new tools for modeling, not simply incremental accumulation of new lines of code or nodes on a semantic/concept map. Such tools can be used to test and validate alternative representations in the same environment. For example, two rival orbital models of earth can be put into the same solar system and tested; in doing so, learners naturally and authentically transform their understanding of planetary orbits from an intuitive explanation to an equation-based structure to a physics-based model. Specifically, they can create an Earth model, generate a hypothesized equation, and then insert a new model Earth and explore force and velocity vectors in an attempt to create a similar planetary orbit. The representation of multiple, but differently conceived, models has helped learners transform their understanding of planetary motion. Modeling environments need to support "epistemic forms and games" not by becoming a general purpose modeling language (e.g., Logo, StarLogo, Boxer, AgentSheets, etc.) or scaffolded construction kits (e.g., Model-It, Stella, etc.). Rather, our system takes advantage of multiple modeling environments, enabling the co-existence of different "forms and games" that can be used to develop the underlying systematic relational structure underlying students' isomorphic models.

PRELIMINARY RESULTS

Our findings have been overwhelmingly positive and are exemplified by the pre- and post interviews that showed a significant improvement in learners' conceptual understanding of eclipses. These findings are demonstrated by "Jason's" development of understanding of an eclipse:

Question posed: What is an eclipse?

Pretest response: I think it has something to do with the day-night sequence. I guess that when the Earth is turning, we see different sides of the moon.

Posttest response: The Moon is going around the Earth, and the Moon is behind the Earth, and the Earth is going around the Sun. The ecliptic and the rotational path intercept at the line of nodes and due to the 5-degree tilt they cross at certain points. If it is a total eclipse, that is, an umbral eclipse, it is beet-red.[1] If it is penumbral eclipse, then it is partial eclipse. It depends on when the Moon is on the line of nodes.

CONCLUSIONS

Building on our OpenSkies™ platform, we have extended our initial prototypes that support students through a learner-centered designed interface that has allowed them to quickly and easily develop the otherwise difficult prospect of creating dynamic 3-D models of the solar system in virtual reality. We have enhanced our software so the students can effectively navigate from perspectives that are similar to the ones they experience everyday, to extraordinary perspectives (from the moon, from the head of a comet, standing on the sun, etc.) so that they will readily "see" the model from perspectives that enhance their understanding. We have added other capabilities that facilitate the student to student and student to teacher interactions around these models. For example, instead of simple chat rooms, where students can talk about the models they have built, we provide students and teachers with the ability to co-construct and co-habit these models, and 2-way audio/video support so they can talk about and present there work from within their virtual models.

The power of our foundational technology, OpenSkies™, and these added enhancements has created a system that minimizes the students' time to learn the software and maximizes the learning of the content. Furthermore, the model has become vastly easier to scale, support, and disseminate. Our work has shown that such a system can be made and used by others.

[1] "Beet-red" is a reference to his additional visualization of the shadow of the moon and its resultant red shadow when a total eclipse occurs.

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