Teaching 3D Modeling and Simulation: Virtual Kelp Forest Case Study

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Abstract. Two classes of graduate students learning 3D graphics and analytic simulation at the Naval Postgraduate School modeled the three-dimensional (3D) shape, structure, imagery and motion behaviors of plants and animals in the kelp forest exhibit at the Monterey Bay Aquarium. Our intended audience includes educators and students of all ages, scientific users interested in composing models in a 3D Web environment, and the general public. The Virtual Reality Modeling Language (VRML) proved to be an excellent medium for capturing diverse models, composing multiple student efforts, and publishing dynamic results publicly on the Web. By focusing on thoroughly modeling a controlled environment, we produced an exemplar 3D graphics site for modeling larger and more sophisticated underwater domains. This project was successfully demonstrated to numerous new users, including 1000 people during the 1998 National Ocean Fair in Monterey. This project serves as an interesting case study on teaching contemporary computer graphics to university students with a wide range of backgrounds.

1 Overview and Motivation

Teaching 3D graphics courses usually includes a mix of theory and practice. Typically a large number of sophisticated geometry and programming concepts must be presented before students can produce visually interesting results. Technical material must be grounded by frequent authoring assignments, in order for new jargon to become sensible and concepts to become clear. Demonstration projects which show interesting animations are an excellent way to "pull" students through beginner and intermediate material.

The Virtual Reality Modeling Language provides a possible solution to these teaching challenges. Because VRML represent 3D scene graphs as an interchange format rather than a program, multiple small VRML models can be quickly composed into larger scenes. This approach permits construction of elaborate and consistent worlds from multiple independently created student projects.

The actual Kelp Forest Exhibit at the Monterey Bay Aquarium is an ambitious and accurate recreation of a signature ocean habitat which exists along many parts of the California coast. Intensely beautiful, this complex and observable system was chosen as the modeling subject for fifteen graduate students in a pair of classes at the Naval Postgraduate School (NPS), also located in Monterey California. Having to model both the imagery and behavior of a dynamic, interdependent and observable system provided an excellent challenge for group effort. Although modeling reality with complete fidelity in real time on commodity personal computers is acknowledged to be beyond the current state of the art, students were nevertheless

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challenged to show what was possible. Posing public demonstration before a national audience as the course-completion exercise provided ample motivation for success as a team.

The virtual Kelp Forest Exhibit project is presented as a case study showing how building group scenes serves as an excellent way to teach and present 3D graphics modeling and simulation. The structure of this paper is organized as follows. First the participants, modeling subjects, teaching goals and target audience are identified. Pertinent VRML attributes of interest are explained in some detail. Elementary physics models for the target environment are derived, with an emphasis on real-time performance and tight integration. Lessons learned during public demonstrations are summarized. Finally teaching considerations are presented, along with conclusions and recommendations for future work.

Figure 1. Entry view of the model gives
simple viewing instructions.

Figure 2. Gallery view. Tank dimensions are
10m (two stories) tall by 19m wide.

2 Participants, Site Selection, Goals and Audience

In the spring of 1998 a total of fifteen graduate students were enrolled in two previously unrelated courses: *Introduction to 3D Computer Graphics using VRML,* and *Analytic Modeling and Simulation.* This was an excellent opportunity to attempt enabling students to work independently on multiple related individual projects, which then might ultimately be combined into a single coherent whole.

Linking two courses in such a way was an ambitious and unproven goal. It became clear early that a compelling subject was needed to stimulate the imaginations and enthusiasm of students to do great things. Thus, selection of the site to be modeled was a crucial design decision. The answer was found nearby.

One grove stands apart from the others. The Kelp Forest exhibit, an aquarium centerpiece, looks so natural many visitors believe they're looking through a window to the bay. It's an illusion designed for both visitors and kelp. The exhibit opens to the sky, and the sunlight streaming majestically through the amber fronds helps the kelp grow. - Monterey Bay Aquarium (MBA 99)

After some class discussion of possible alternatives, our shared objective became to model the three-dimensional (3D) shape and motion of plants and animals in the Kelp Forest Exhibit at the aquarium. The first group of students were computer science students learning how to use the Virtual Reality Modeling Language (VRML) to describe the 3D shape and appearance of the tank and its inhabitants. The second class of students were in cross-disciplinary curricula (with no 3D graphics background) who learned how to apply physics-based modeling and analytic simulation techniques to recreate the hydrodynamics flow and swimming behaviors seen in the tank.

This choice of site proved to be a good one. The Kelp Forest Exhibit exemplifies a large diverse environment that permits close, repeated scrutiny. Since the exhibit itself is a carefully constructed recreation of an actual ocean habitat, tank dimensions are well specified. Tank behaviors (motion by fish and the surrounding water) can be quantitatively approximated by visual inspection and verified by biologic models. One design issue was that tank population is extremely large, with over a thousand fish, plants and other animals. Accurately simulating so many independent entities did not appear to be possible using commodity personal computers, but enough tank inhabitants might be modeled to present a satisfactory user experience. Since the upper limit on tank population was very large, and since no networking was used to distribute computational load, we expected to stress the performance level of all target display machines (personal computers, with or without 3D hardware acceleration). The relatively slow speed of tank inhabitants was an acceptable match for potentially slow rendering frame rates.

Determining the intended audience is an important design decision which is used throughout project development to determine user experience, interactivity, and interface (Pearce 97). Knowing the intended audience also helps determine the depth and breadth of the modeling effort, both for 3D models as well as physical simulations. Again we looked nearby for possible answers. Special characteristics of the Monterey Bay area include three dozen institutions engaged in ocean-related study and research. Regional scientists and their institutions are often partnered in close relationships with primary, secondary and college students (Brutzman 95). Assuming success, this project might serve as an exemplar for VRML use in science and education, particularly for composing diverse underwater datasets and models in a 3D Web environment. Thus we decided that our intended audience was quite broad, including:
• Educators and students of all ages
• Scientific users visualizing and composing models and datasets
• General public interested in underwater scenes or 3D graphics

An interesting opportunity which presented itself early in the teaching quarter was the National Oceans Conference (NOC 98), conveniently scheduled at the end of the classes. The group agreed that public demonstration at this event would be the "final exam." Having tangible deliverables and an actual audience to work for proved highly motivating. Knowing that time constraints were inflexible simplified many design choices throughout the quarter. Early decisions regarding subject goals plus intended audience provided a clear "finish line" for students. These clear objectives were a key element in achieving ambitious teaching goals.

Defining these various attributes of success in terms that everyone understands is always an important prerequisite if the pieces of a group project are to fit together. Furthermore, choosing a meaningful and accessible world enabled the graphics and the physics simulations to proceed in tandem. Finally, one

other design constraint was consciously imposed: the site must be "cool." In the graphics community, "cool" can be considered a quantitative term, defined recursively: it means compelling interactive 3D content that provokes participants to say, "Cool!" Our results passed the "cool" test, as exemplified in the signature image of Figure 3.
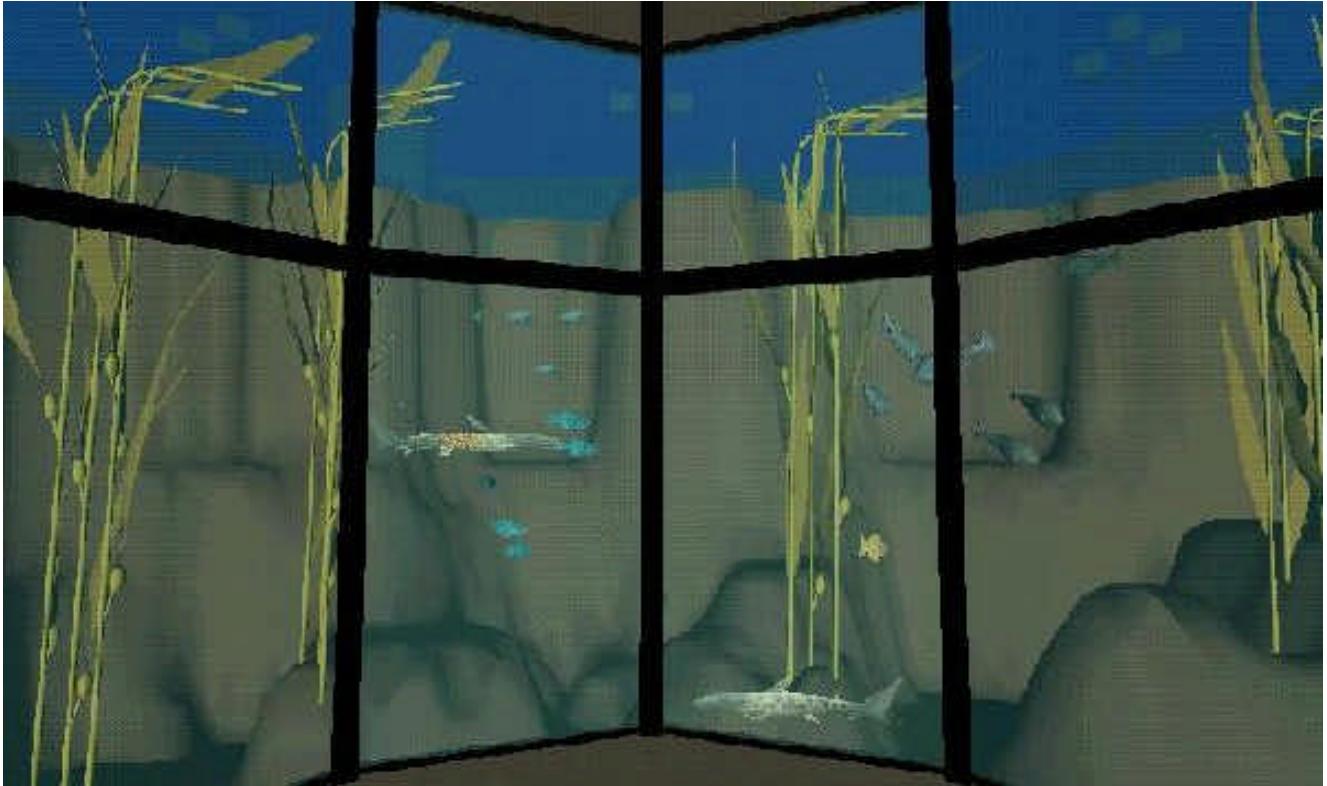

Figure 3. Swaying kelp, swimming sharks, schooling sardines and fish provide a compelling view.

3 Teaching 3D Graphics using VRML

Teaching 3D graphics has evolved, just as the underlying hardware and software technology has evolved. Exponential increases in hardware capabilities have paralleled steady improvements in rendering algorithms, software languages and application programming interfaces (APIs). In part due to continually rapid technical progress, SIGGRAPH's Education Committee has not published formal teaching standards for 3D-graphics curricula. Some educational resources are available online (www.education.siggraph.org) and improvement possibilities remain a perennial topic (Owen et al., 1994).

Historically, introductory graphics courses focus on tedious low-level programming which requires so much language and compilation overhead that the actual graphics objectives tend to become obscured. Higher-level alternatives to teaching 3D graphics use expensive authoring programs to draw scenes. Unfortunately, learning to use such tools often means devoting much time to unique user-interface requirements, again obscuring the underlying graphics concepts of interest.

VRML is an international standard (ISO 97) that has extended the Web to three spatial dimensions. VRML-based 3D Web browsers are freely available, typically embedded inside 2D browsers or are launched as independent applications. Primarily designed as an interchange file format, VRML models are structured as scene graphs in which grouping, transformation and selection nodes as interior branching nodes, while geometry, shape and accompanying render attributes are leaf nodes. VRML scenes are capable of describing a wide range of 3D content.

VRML models are declarative descriptions of 3D content (i.e. *what* to draw) as opposed to imperative programming language commands (i.e. *how* to draw). Node and field names correspond exactly to 3D graphics concepts of interest. Because the scene graph paradigm is common, VRML examples can illustrate a great number of 3D graphics topics and provide an accurate conceptual foundation for later student work using specific APIs or authoring tools. Elimination of teaching overhead for programming languages, compilers or special API toolkits has shown us that *even students without programming experience can learn VRML successfully*. A further significant comparison is that two quarters of introductory API programming (e.g. OpenGL) are needed to present the same number of concepts covered in one quarter using VRML.

An open standard, VRML might be considered similar to Computer-Aided Design (CAD) file formats, but without proprietary restrictions or expensive software licensing requirements. Additional benefits of teaching VRML as an introductory course include portability across multiple computing platforms, plain text editing, simple e-mail or Web distribution of interactive models. These factors make VRML an excellent choice for teaching graphics concepts.

A number of excellent books are available which present VRML 97, often node by node. We have used the *VRML 2.0 Sourcebook* (Ames, Nadeau 97) several times with consistently excellent results. The most important attribute of any such textbook is an extensive collection of examples which students might inspect, modify and adapt. NPS is organized on a quarterly schedule, typically four classes per week, so covering about one chapter per meeting day has been an aggressive but achievable pace. A large variety of ancillary and related material is available online to supplement core teaching topics.

One essential authoring tool is a parser to perform error checking, since VRML syntax can be difficult for beginners. VRML browsers typically provide such support by identifying errors in console windows, though using such diagnostic messages for error localization can be cryptic. Furthermore, browsers usually attempt to be forgiving of errors, but ignoring or misinterpreting malformed inputs can lead to mysterious results. Students who don't eliminate syntax errors and misunderstand the underlying graphics concepts tend to author by trial-and-error techniques, which is (obviously) undesirable. We have found that the freeware syntax-checking tool *Vorlon* (Trapezium 99) provides thorough and accurate results. Vorlon is Java-based, cross-platform and runnable from the command line. Our course recommendation (and source distribution policy) is to maintain zero file errors and zero file warnings over time. This is accomplished by automating *Vorlon* syntax checking (and then fixing bugs) whenever building binary distributions of the kelp site.

Student projects written in VRML are immediately viewable when distributed via diskette or as electronic mail attachments. Serving VRML via http server may require addition of the line

`model/world .wrl .wrz` to the server MIME type configuration; see [FAQ 99] for details. For the kelp forest project, interim and final models added to the scene were kept individually accessible via the *Models* page. This was a useful collaborative approach that let students ask questions, post solutions, add comments and note problems as we proceeded.

The sheer volume of concepts needed to construct interesting 3D models makes it difficult for beginners to create meaningful content. Advanced students have the skills to produce interesting models, but their work typically does not survive long because it requires special configuration knowledge to compile and view. Using VRML as an entry-level or intermediate-level computer graphics course works well. Use of VRML and this project have been especially useful for supporting the cross-disciplinary goals of the new Modeling, Virtual Environments and Simulation (MOVES) major here at NPS (Zyda 99).

Since graduate school permits some leeway, grading does not have to be based on tests and can instead be based on individual or group modeling projects. We have found that student understanding (and enjoyment) of technical topics is greatest when they must apply conceptual techniques first-hand to produce working demonstration programs. Ordinarily, students are encouraged to select individual projects. Given these special circumstances, the two classes chose to work together as a group on a single ambitious project. Often this means that stronger students might dominate the efforts, but splitting up tasks into discrete assignments let each student retain responsibility for learning sufficient VRML to model their assignment well. The slogan "demo or die" provokes strong peer motivation and good cooperation.

4 Modeling Behaviors and Physics

Models are representations of reality that help us understand and describe the world around us. The kelp forest aquarium exhibit is itself a full-scale model recreation of a fascinating, complex shallow-water habitat. Choosing a closely observable system let students study and record quantitative data to keep physical, behavioral and geometric models realistic.

> *Pumps push more than four thousand gallons of seawater a minute through jets placed to generate natural currents in the exhibit. And the kelp here sways in a surge--vital to the plants--created by a special wave machine.* (MBA 99)

We have attempted to accurately model the physics of water motion in the tank. The primary driving force is a positive-displacement (i.e. piston-driven) circulation pump on the top deck. In order to accurately describe the physics of water motion, as well as the locations of plants and behavior of animals, we must carefully describe tank dimensions using a well-defined coordinate system. Figure 4 provides a top-down schematic of tank layout. The various "K" sites in the tank are the aquarium-numbered kelp plants, and coordinate points A through M were added for convenient reference. The positive-displacement pump (reportedly designed and constructed by David Packard) is at the surface above point I. Contour lines show the steepness of the rear rock wall, as well as free-standing boulders. Seawater circulation pipe inlets and outlets penetrate the wall between points G and H. These high-capacity penetrations are located behind a rock face to disperse the flow in a variety of directions.
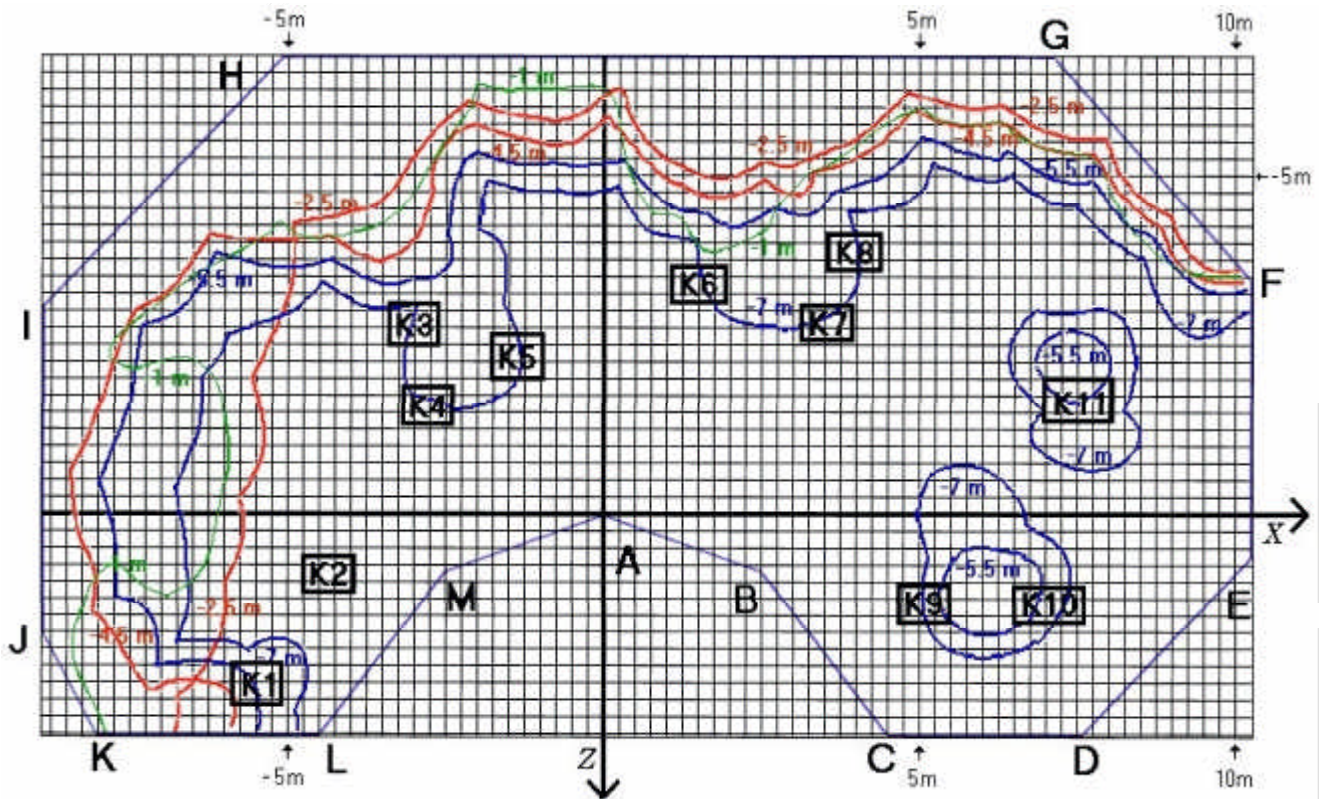
Figure 4. Tank map provided rock topography and precise locations of landmark kelp plants.

Local coordinate systems must be defined for each moving entity and each hydrodynamics locale; an example is shown in Figure 5. A perspective view showing coordinate system conventions relative to the tank's front-window geometry is provided in Figure 6.
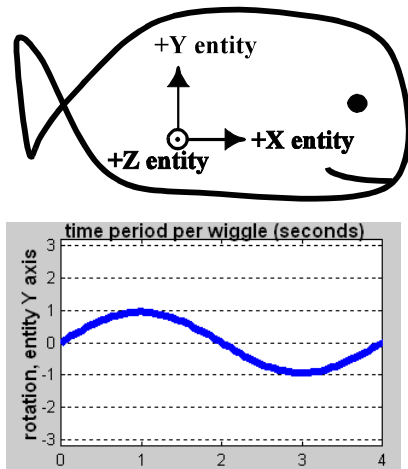

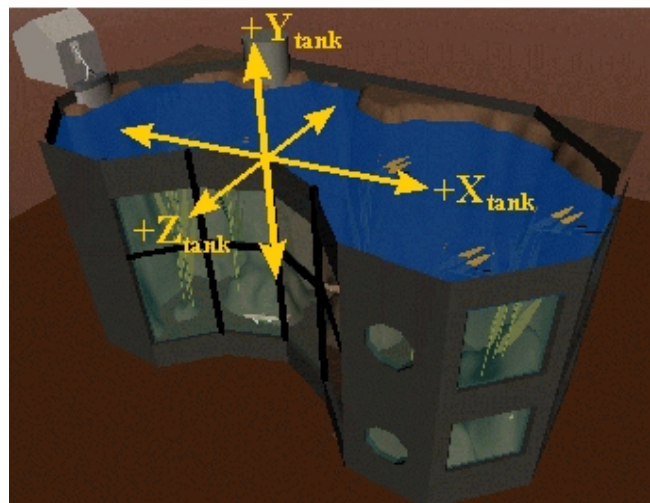**Figure 5.** Local coordinate systems are defined for each moving entity and hydrodynamic-flow locale.

Figure 6. A global tank coordinate system is essential for integrating multiple models accurately.

From the beginning we were aware that one of the most difficult problems in this simulation was that of the hydrodynamics of the Kelp Forest tank. The class was challenged to create a true-to-life model of the flow within the tank, and to code the analytic model in VRML as part of the overall simulation without severely slowing down the overall runtime of the model. Two problems were particularly difficult:

1. Exact modeling of the hydrodynamics might prove too computationally intense, in effect slowing the simulation and preventing real-time playback.

2. The tank was not a simple or regular polygon. The sides consisted of irregular rock formations which in combination with plant-life might create an overly complex pattern of water flow.

Not knowing such a model in advance while being able to directly observe the final results made this problem a tantalizing challenge for engineering students.

We learned from conversations with aquarium personnel that the positive-displacement piston pump was designed and driven to generate a one-foot standing wave. Using this knowledge, recording experimental observations, and applying previous experience with wave mechanics, students derived several basic equations of motion for water in the tank. About six weeks were necessary to correlate tank observations, numerous hydrodynamics discussions and a variety of theoretical ideas into a working model.

Decomposition of horizontal and vertical components proved to be the key to a tractable analytic solution. Equations 1 and 2 (illustrated by Figures 7 and 8) were observed to provide an excellent approximation to the peak-to-peak pump-induced oscillatory motion affecting fish and plants throughout the tank.

$$X_{displacement\ max} = \frac{12m - |Xcoordinate|}{12m} \times .305m \quad (1)$$

$$Y_{displacement\ max} = \frac{-8.5m - Ycoordinate}{8.5m} \times \frac{Xcoordinate}{12m} \times .305m \quad (2)$$
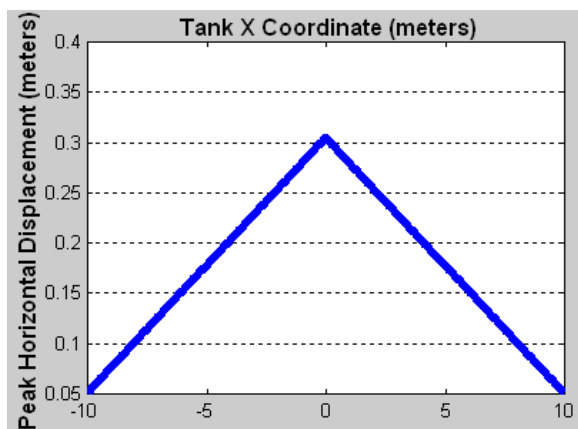

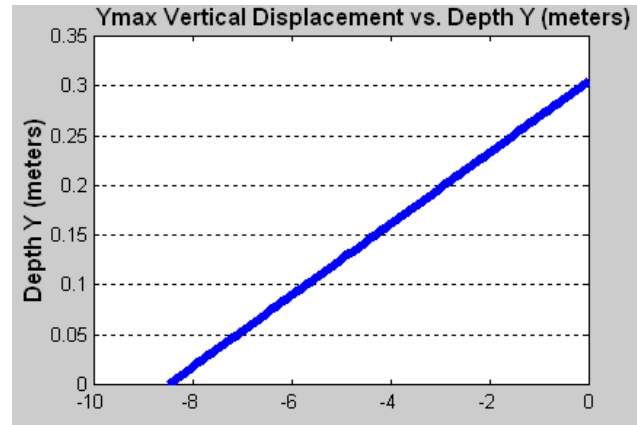**Figure 7.** Maximum peak-to-peak lateral movement due to circulation-inducing piston pump.

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Figure 8. Maximum peak-to-peak vertical displacement (along left and right walls) versus depth.

Partitioning the scene into moving locales was the key to implementing the hydrodynamics model efficiently in VRML. The integrated simulation of multiple physical processes thus appears to be modeled correctly at an adequate degree of resolution. The final approximation successfully reproduces realistic results in real time. Considered from a scientific and educational perspective, reality is much more challenging than virtual when modeling actual locations and behaviors.

5 Lessons Learned from Public Demonstrations

We continue to learn a number valuable lessons through frequent demonstration. Over 1000 people visited the kelp forest exhibit during the 1998 National Oceans Fair. About half of our visitors took the time to sit down and try exploring this virtual space - interestingly, almost all were school-age children. Only a few adults were willing to try, apparently due to apprehension regarding high technology rather than lack of interest in the subject material. All participants became comfortable with site navigation within the first minute. Typical visits are 3-5 minutes, though some children decided to "play" and explore for 10-20 minutes. Touring the site invariably provokes numerous questions on a complete spectrum of topics including biology, graphics, computers and ecology.

Figure 9. Students guided 500 visitors (mostly children and young adults) through the Virtual Kelp Forest exhibit, as part of the 1998 National Oceans Fair in Monterey.

Insistence on a simple interface during the design phase paid off: "page down, wait & watch" for next viewpoint (Figure 1) makes sense to newcomers and allows simple navigation. Viewpoints include entry scene, birds-eye view, various vantage points around the tank, and several moving entities (which are also handy for unattended demonstration). Choosing from the menu bar of fifteen viewpoints also enables quick navigation to features of interest.

More detailed exploration through clicking or dragging the mouse led to consistently bad results, apparently due to public unfamiliarity with 3D navigation. Establishment of simple and consistent navigation metaphors remains an important challenge for 3D graphics. This accessibility problem is so severe that perhaps everyone can be considered "access impaired" in most 3D scenes. Perhaps ubiquitous availability of VRML scenes on the Web will stabilize navigation conventions for 3D graphics, in the same way that ubiquitous availability of HTML pages stabilized 2D hypermedia navigation conventions in the early 1990s.

Two comments predominate in verbal and written critiques of this project, especially among children. First, the kelp site is "cool," people enjoy the experience and are enthusiastic about what they see. Second, Lefty and Lucy Shark are definitely the most popular inhabitants (Figures 9 and 10). Many people are also struck by the flocking sardines, particularly the fish-eye wide field of view that follows the lead sardine up and down the tank.

Figure 10. Lefty & Lucy Shark are virtual tour guides, leading visitors throughout the kelp forest.

Figure 11. Actual leopard sharks also swim throughout the kelp forest tank.

Numerous people have asked to download the site (10 MB graphics and imagery, 20 MB video clips). Nevertheless follow-up reports from these contacts are seldom received, indicating that few people are actually willing to download extensive content for offline viewing.

Currently scene navigation and interactivity consists of numerous static and moving viewpoints, along with browser-supplied SEEK and EXAMINE modes. This simple interface is designed to minimize confusion and provide a sense of presence for the viewer. Further interactions between 2D and 3D are an inviting future task, since extensive hypermedia details on physics, biology, video clips, and associated references are already collected on the 2D portion of the site. Addition of audio narrative and ambient

sound cues might also help, although this additional multimedia load might excessively overburden slower personal computers. Clearly many student projects of broad interest remain to be pursued, and "cool" remains a moving target.

6 Teaching Considerations

This project remains active and is used in several classes as an opportunity for further projects. Pedagogical lessons learned of general value include:
• VRML is an excellent language for teaching beginning and intermediate 3D graphics concepts
• frequent project demonstrations benefit students, visitors and sponsors
• modeling the real world makes abstract geometric and rendering concepts more intuitive
• documented examples by prior students provide a rapid boost to new students
• learning goes way up when students are directly involved producing an exciting project
• Web publication attracts new students from other fields interested in applying 3D as a tool

Typically the dominant teaching factor in 3D graphics curricula is choice of student programming language and API. Students in a single-quarter VRML class typically cover nearly the same scope of graphics material a two-course introduction to OpenGL (the most common C++ rendering API). VRML is also an excellent interchange format for integrating diverse contributions. This includes work originally authored using other languages, APIs and file formats. We currently have VRML projects that integrate Java, C++, Java3D, ECMAScript (formerly JavaScript), Matlab, Performer, OpenInventor, a handful of Computer Aided Design (CAD) model formats, and various specialized 3D authoring tools. Interoperability means that students can use their software applications of choice to explore a problem and produce results, then export the interactive scene to VRML to continue enjoying content composability and publication on the Web.

Establishing intuitively understandable user interfaces remains a major challenge. A general lack of 3D interface conventions is an impediment to rapid use. Both experts and nonexperts typically approach new 3D applications clumsily, using trial-and-error attempts to discover how to interact. Furthermore, expert expectations are often contradicted by actual user testing. In our experience, usability progress has only emerged through ongoing demonstrations and continued development. Improving interfaces by establishing common navigation conventions is a rich area for further student work.

7 Future Work and Conclusions

Two factors have gated the broad availability of online 3D graphics: hardware acceleration and compatible software interchange. The hardware problem is rapidly being solved by the inevitable progress of chip manufacturers: 100 million graphics-accelerated personal computers were shipped in 1999. Meanwhile, following 25 years of typically closed approaches for 3D software, the availability of VRML 97 provides an interoperable interchange format that is compatible with all types of hardware, operating systems and software APIs. This means that 3D content might finally escape the boundaries of the graphics and gaming communities, becoming a output medium accessible for use by the world at large.

The Extensible 3D (X3D) specification is an exciting new area of work, expressing the geometry and behavior capabilities of VRML using the Web-compatible tagsets of the Extensible Markup Language (XML). The X3D Task Group is designing and implementing a next-generation extensible 3D graphics specification (www.web3D.org/x3d.html). X3D attributes include simpler validity checking, componentized browsers for faster downloads, flexible addition of new hardware extensions, and better script integration with a variety of programming languages. Efforts are underway to automatically import the full set of Virtual Kelp Forest models into a Java3D scene graph and then export X3D files. This task exercises most 3D and animation aspects of these scene-graph specifications, demonstrates syntax checking with autotranslation, and provides a challenging conformance/performance site for demonstrating exemplar high-end content. Additional work on streaming many-to-many behaviors and integrating 2D-3D content provide further worthy challenges that are best demonstrated through such examples.

In conclusion, this paper describes a successful group project with interesting implications for teaching 3D graphics. Real-world physics and large numbers of independent entities can be simulated in real time on commodity personal computers. Developing cross-disciplinary virtual worlds with an emphasis on reality provides students with excellent insight, enthusiastic motivation and useful learning exemplars.

Acknowledgments

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