

# Scientists in Wonderland : A Report on Visualization Applications in the CAVE Virtual Reality Environment

Carolina Cruz-Neira†, Jason Leigh, Michael Papka, Craig Barnes, Steven M. Cohen, Sumit Das, Roger Engelmann, Randy Hudson, Trina Roy, Lewis Siegel, Christina Vasilakis, Thomas A. DeFanti, Daniel J. Sandin

Electronic Visualization Laboratory,  
Department of Electrical Engineering and Computer Science  
University of Illinois at Chicago  
Chicago, IL 60680

## Abstract

*This paper presents the experiences at the Electronic Visualization Laboratory (EVL) in introducing computational scientists to the use of virtual reality as a research tool. We describe our virtual environment, the CAVE. We then describe several applications currently being developed at EVL using the CAVE and conclude with a discussion on possible research paths to follow in making virtual reality an effective tool for visualization.*

## 1. Introduction

Traditional computer graphics has typically required that scientists look through a restricted window (the computer screen), to view images that depict their research data. Virtual Reality (VR) on the other hand, offers scientists the means to leap through that window and physically engage their experimental environment.

## 2. The CAVE

The CAVE was originally conceived in 1991 by Thomas DeFanti and Dan Sandin (co-directors of the Electronic Visualization Laboratory) and implemented by Carolina Cruz-Neira (currently a Ph.D. student). The intent was to design a VR system that avoids the current limitations of VR systems such as poor image resolution, isolation from the real world, and inability to simultaneously share virtual experiences with multiple users.

The CAVE is a projection-based VR system (see Figure 1). The illusion of immersion is created by projecting stereoscopic computer graphics into a cube composed of display-screens that completely surround the viewer. It is coupled with a head and hand tracking system to produce the correct stereo perspective and to isolate the position and orientation of a three-dimensional input device. A sound system provides audio feedback. The viewer explores the virtual world by moving around inside the cube and manipulating objects with a three-button wand-like device.

†E-mail: cruz@bert.eecs.uic.edu

The CAVE blends real and virtual objects in the same space so that a person has an unoccluded view of his/her own body as it interacts with the virtual objects. A detailed discussion of the CAVE can be found in[2].

## 3. The Applications

We invited scientists from various disciplines and research institutions to use the CAVE to visualize their research data. The purpose of this was first to thoroughly test the capabilities of the CAVE and second to gain some understanding of the kinds of scientific data that can benefit from being visualized in a virtual environment. This also served as an informal user study to discover new features that may be useful to scientists in developing VR applications. This effort resulted in the construction of applications like architectural walk-throughs, to completely novel experiences, like flying through the universe to witness the Big Bang. The following then is a compilation of some of these applications.

### 3.1 Architectural Walk-throughs

**Collaborators:** Roger Engelmann, Terry Franguiadakis, Kathy O'Keefe, Lewis Siegel, Donna Wolf (University of Illinois at Chicago).

Architectural walk-throughs have been one of the typical applications for VR. We are interested in using the CAVE for walk-throughs of indoor and outdoor architectural environments.

#### 3.1.1 CAVE Visualization

Most of the architectural models we use are stored in the standard DXF file format. As a first step, we developed a DXF-to-CAVE translator to bring models in DXF format into the CAVE. One of the features of the translator is that it will interpret the data and match it to the CAVE's geometry. One of the visualizations depicts a model of a house with several furnished rooms. Another one is a reconstruction of downtown Chicago from the database

supplied by the architectural firm of Skidmore, Owings and Merrill. Users can navigate through the space either by physically walking around in the CAVE or using the wand as a control device to move greater distances. We use a selection ray to pick objects for manipulation or to point at places we want to go. Objects intersecting the ray can be selected, and their textures and colors can be modified. For fly-throughs in large environments, like the Chicago database, the ray indicates direction of the flight. We provide auto-piloted exploration of the environments. Predefined paths can be set and used to acquaint users with the space before they attempt to manually explore the environment.

### 3.1.2 Discussion

One advantage of the CAVE for architectural walk-throughs is that the entire body of the user is inside the virtual space, rather than just the user's eyes. Thus, when users look around, they can see the exact location of their own legs, arms and other parts of their body in relation to the virtual space. This feature of the CAVE is very important for testing the ergonomics of architectural designs, which is one of our major areas of research. The CAVE offers a great opportunity for experimenting with navigation techniques in large spaces. Because of the surrounding walls, the user has a reference frame for the orientation of the virtual world. We believe this fact will reduce the disorientation that occurs in fast changes in the viewer's location in the virtual space. We are currently using the selection ray technique to select a far away place and quickly move to that location. A more formal analysis of the usage of this or similar techniques is being planned.

## 3.2 The Cosmic Explorer

**Collaborators:** Michael Norman, Deyang Song (National Center for Supercomputing Applications), Trina Roy (University of Illinois at Chicago)

The Cosmic Explorer is a research tool for exploring the stages of the evolution of the Universe. We visualize the result of numerical simulations to allow the exploration of the formation of the universe, astrophysical jets, and colliding galaxies.

### 3.2.1 CAVE Visualization

In the CAVE visualization, each galaxy is depicted as a point in three dimensional space; the color of each point represents the age of the galaxy. Other representations for the galaxies, such as cubes, tetrahedrons or textured polygons, were also considered but rejected because they compromised the rendering speed or did not contribute additional information to the experience. We settled for the single pixel point representation because it was the fastest and most intuitive model. The animation shows the evolution of the Universe since the Big Bang. It starts as a

single mass that explodes and expands in front of the viewers until it completely surrounds them, filling the CAVE space. The user can pause the animation and travel through the data to explore far away galaxies or step back to view the whole universe structure from a distance.

### 3.2.2 Discussion

The Cosmic Explorer is a good example of a human-oriented paradigm for exploring large data sets with spatial and temporal information. We allow users to explore the simulation data as they might explore a physical place. The effects of the clustering galaxies were strongly depicted in the CAVE because of the panoramic view provided by the surrounding projection screens. Memory requirements were the major concern when operating the Cosmic Explorer. The visualization involved a large data set of 30 Mbytes, which is only one-tenth of the actual simulation data. In the current implementation of the CAVE, we have to load the entire data set in memory for the interactive experience. In order to visualize the complete simulation data set, we would need at least 300 Mbytes of RAM! Large datasets are common across many simulations. Techniques to manipulate and select portions of data for CAVE display will have to be developed. Additional functions such as volume selection, successive refinement of the images and VCR-like controls would be beneficial to improve the usability of the application for further astrophysical research.

## 3.3 The Fractal Explorer

**Collaborators:** Randy Hudson, Alan Verlo, John Hart (University of Illinois at Chicago), Jim Crutchfield (Santa Fe Institute).

The purpose of the Fractal Explorer is exploration and education. It shows CAVE users what fractals and strange attractors look like and how they are made. It also allows them to manipulate the equations that generate these objects to discover how this causes significant changes in their structure. At SIGGRAPH'92, the sample strange attractor was the Lorenz attractor, shown in Figure 2, and the sample fractal was the Sierpinski tetrahedron.

### 3.3.1 CAVE Visualization

Three-dimensional strange attractors are usually modeled as points or lines. To give proper depth cues for VR, such as occlusion, shading and perspective distortion, new surface models were developed that used sensible surface normals for these objects [3]. Each element of the Sierpinski tetrahedron was modeled as a small tetrahedron. A new way of exploring strange attractor space was also developed in the CAVE. A ribbon of a given length is anchored to the end of the wand, and allowed to be drawn into the flow field. The user can move the anchored end anywhere in space, while the attractor tries to draw the

ribbon in by the other end. The orientation of the ribbon, a lit membrane stretched between two neighboring trajectories, reveals the approximate direction of spreading in the flow field, while its body, as the wand is moved throughout space, reveals the paths the trajectories follow into the attractor from different locations. It is important to note that the development of this tool was very natural in the CAVE, where one could move around the data, and manipulate the control device in all three dimensions. The virtual sphere interface method for two-dimensional windowing environments [5] has been changed and used as an intuitive way to rotate objects in the CAVE.

### 3.3.2 Discussion

The Fractal Explorer has been cited by most users as being extremely effective at giving the user a convincing three-dimensional, immersive feeling. However, disparity is too great when objects are very close, unless they are kept small. For proper exploration, the user ought to be able to hold the object very closely (right up to the eyes) and examine the detail clearly. Perhaps a virtual microscope or telescope tool can be designed to implement this function. The current wand controls limit the number of possible interactive combinations needed by this application. It is therefore clear that other interfaces must be built to provide the user with as many control options as those offered by graphical user interfaces on workstations. These interfaces must still be natural and intuitive to use in an immersive environment.

### 3.4 Full Configuration Interaction on the Intel DELTA

**Collaborators:** Rusty Lusk, Robert Harrison, Eric Stahlberg (Argonne National Laboratory), Steven M. Cohen (University of Illinois at Chicago).

Scientists at Argonne National Laboratory are interested in developing efficient algorithms for coordinating jobs on highly parallel computers. Their main goal is to minimize job execution time by maximizing processor utilization and information throughput. This application is a visualization of a job executing on 128 processors of an Intel Touchstone DELTA parallel supercomputer. During job execution, the memory requests of each processor and the times in which processors remain idle are recorded and saved in a data file.

#### 3.4.1 CAVE Visualization

The application involves a visualization of the 128 processor array arranged in a grid centered in the CAVE environment. Inter-processor message passing, in which processors either send or request information to or from other processors, is portrayed using event arrows which bounce from processor to processor depending on the

message traffic. Processors are colored depending on whether they are free to continue processing or whether they are idle, waiting for other processors to meet their request. Waiting processors are denoted by parabolic red arrows drawn from the requester to the requestee. The application also includes another visualization in which slices of the 128 processor grid are stacked from top to bottom, each slice denoting a separate time step during job execution. In this visualization, the scientist is able to observe and study message traffic, processor throughput, and processor utilization. This helps the scientist gain a greater understanding of a job's execution history and helps determine the efficiency of different job execution algorithms.

#### 3.4.2 Discussion

Future directions for this research include the development of interactive methods to step through time segments of job execution, and the display of job execution parameters in the multi-dimensional Parallel Coordinate Geometry [1].

### 3.5 Mapping Cognitive Function with Subdural Electrodes and Registration of Cerebral Evoked Potentials on 3D MRI

**Collaborators:** Vernon L. Towle, Robert Grzeszczuk, Martin Ryan (University of Chicago), Steven M. Cohen (University of Illinois at Chicago).

This application is an example of sensory evoked potentials mapped onto a 3D surface model of a human head. Included in the model is a 3D brain surface derived from MRI data and polygonalized to produce a real-time graphics model. The outer head model is a clay model scanned using a Cyberware laser scanner.

#### 3.5.1 CAVE Visualization

The voltage potentials are measured off the head using 21 separate electrodes. The electrodes measure brain activity. The recordings were made during an experiment in which a patient is shown a checkerboard pattern. In addition, recordings were made during a stimulation of the tibial nerve. The resultant voltage potentials were recorded over brief time intervals (approximately ten milliseconds) and the range of voltages is mapped onto a color scale. The color values are then placed on the head model and interpolated producing color gradations. Areas of increased, decreased, and static brain activity can then be visualized. This application is effective in revealing the overall spread of activity in the brain. One important aspect of the application is that it plays back the voltage history in real-time, and scientists who have worked with EEG data find this very exciting.

### 3.5.2 Discussion

A useful aspect of this application is that different electrodes are assigned different musical instruments producing sounds whose pitch is dependent upon the voltage levels. The resultant musical composition is comprised of complex instrumentals with melodic and rhythmic components which help differentiate the electrodes by drawing on our ability to recognize complex patterns in sound. The user can learn to associate these audio patterns with specific configurations of brain activity and can recognize when these configurations emerge. Future directions for this research include the development of new methods for manipulating the head model, the extension of exploration into various structures of the brain such as the visual cortex, and the incorporation of other recorded data for more localized exploration of excited brain areas during stimulus/response experiments.

### 3.6 Modeling of Piezoelectric Crystal Resonators

**Collaborators:** Tom Canfield, Mark Jones, Paul Plassmann (Argonne National Laboratory), Michael Tang (Motorola, Inc.), Craig Barnes (University of Illinois at Chicago).

Piezoelectric crystals are an important component in electronic appliances such as computers, cellular phones, and pagers. To be useful, these crystals must resonate in a particular vibrational mode at a specific frequency over a wide range of temperatures. To reduce product development time, engineers need to be able to model the behavior of piezoelectric crystals. In the past year, extensive collaboration between Argonne and Motorola has resulted in the development of algorithms and prototype software to model these crystals on massively parallel architecture's such as the Intel DELTA.

#### 3.6.1 CAVE Visualization

The CAVE visualization of the crystal consisted of the geometry of the crystal and a set of different parameters which represent the crystal's response to different thermal and vibration modes. The thermal mode examined how the crystal expands in reaction to increased temperature. The vibration mode explores how the crystal deforms under a particular vibration mode. For both the thermal and vibration mode the crystal's geometry is altered in response to different stimuli. The two different modes of the crystal, thermal and vibration, are linked to the CAVE's wand. In thermal mode the wand becomes a virtual blowtorch. If the user presses a wand button a particle stream emits from the tip of the torch to simulate heat flow. The crystal expands in response to the heat and contracts when the blowtorch is turned off. In vibration mode, the wand is modeled as an electrical probe which emits a lighting bolt from the tip of the probe, to simulate

electrical stimulation of the crystal which then undergoes a vibration distortion.

#### 3.6.2 Discussion

This simulation while visually interesting, did not really benefit from using VR techniques in its current state. The object is viewed from the outside looking in because the crystal is solid, therefore looking at it from the inside out does not make much sense, although it is interesting to note that at Supercomputing'92 most users positioned the crystal so that they were in the center of the crystal looking inside out. A better use of VR techniques could be achieved by changing the simulation so that the internal propagation of both thermal and vibration effects could be visible from the inside looking out.

### 3.7 Modeling Superconductors on Massively Parallel Computers

**Collaborators:** Mark Jones, Paul Plassmann (Argonne National Laboratory), Michael Papka (University of Illinois at Chicago).

High-temperature superconductors have an immense potential in today's technological world, but a greater understanding is needed to extract this potential. Their recent discovery has spawned an interest in the modeling of these materials. Researchers at Argonne National Lab have developed a three-dimensional model of high-temperature superconductors. This model was then coded to run on a massively parallel supercomputer. The current visualization of the model in the CAVE displays the vortex structure of a cell.

#### 3.7.1 CAVE Visualization

The data used in the CAVE visualization was a three-dimensional lattice of values from which an isosurface is generated. The isosurface is then filtered through a triangular reduction algorithm for real-time display and manipulation in the CAVE environment.

#### 3.7.2 Discussion

The intention of this visualization was in part a test to evaluate whether the CAVE could provide more insight to the still unsolved problem of graphically representing superconductors. Superconductors have a crystalline structure that replicates itself in three dimensions. For a better visualization, the individual data set is replicated throughout the CAVE's virtual space, and hence completely surrounding the viewers. This replication mode makes use of the successive refinement technique; the longer the user holds a fixed position, the more cells are replicated. Figure 3 shows a refined image with several hundred replicated cells. While the visualization in the CAVE has not led to a surprising new view of high-

temperature superconductors, it has addressed some of the problems of such types of visualization in a virtual environment. We are currently working on a new simulation that includes vortex motion.

### **3.8 Molecular Dynamics of Membrane Protein and Receptor Protein Binding**

**Collaborators:** Edwin Westbrook (Argonne National Laboratory), Christina Vasilakis (University of Illinois at Chicago).

The cholera toxin is a mysterious and, until recently, elusive macromolecule which has infected and killed people for the past 150 years. Treatment of cholera would be aided by a thorough understanding of the mechanisms by which the toxin infects and quickly destroys a membrane. Edwin Westbrook, our collaborator in this project, is one of the pioneers in solving the structure of the cholera toxin. His research results describe the cholera toxin structure and its dynamics. Still unsolved however is the problem of how the cholera toxin invades the external membrane of a healthy cell.

#### **3.8.1 CAVE Visualization**

This project uses the CAVE as a visualization tool to depict a theory of how the cholera toxin transports an intact protein through a target cell's external membrane, thereby intoxicating the cell. The cholera toxin is represented as two basic structures: a red doughnut-shaped unit representing the receptor binding domain and a smaller yellow drop-shaped unit representing the active toxin enzyme. The colors are arbitrary and help the viewer distinguish between the two main components. The CAVE viewer witnesses the two stage process of the infection of a membrane. The first stage, the recognition process, occurs when the toxin approaches the target cell and finds a place where it can successfully attach itself, as shown in Figure 4. Once the molecule has "docked", it begins the second and lethal stage of infection by penetration. Once the yellow enzyme is inside the cell, a chain of events occurs, which will lead to dehydration and eventually death of the infected person.

#### **3.8.2 Discussion**

This view of the transportation of the cholera toxin can be studied from a new and otherwise not so easily accessible point of view by virtue of the CAVE. The viewer can walk around the target area of the membrane and examine it. In doing so he/she can also experience the entire two stage process described above by watching the binding domain approach the cell layer, and by peering through the hole through which the toxin enters the cell membrane. The viewer can watch the entire process from either above or below the membrane, or even the middle of it. Viewers at the SIGGRAPH'92 conference commonly

watched the simulation by alternating the views from above and below the membrane. They reported that, in this way, they strongly experienced the three dimensionality of the structures.

### **3.9 Regional Scale Weather Display**

**Collaborators:** Ian Foster, John Michalakes, Rob Neely (Argonne National Laboratory), Carolina Cruz-Neira, Michael Papka (University of Illinois at Chicago).

Understanding the weather and the way weather works is an on-going area of scientific research. Computer Scientists at Argonne National Laboratory have been working on the NCAR/Penn State Mesoscale Model. This model generates simulation data of weather systems over the western region of North America.

#### **3.9.1 CAVE Visualization**

A triangular mesh representing the western region of North America and the Pacific ocean is used as the base frame in the CAVE to superimpose simulation data of land usage, soil temperature, snow cover, wind velocity, and water vapor. Users explore the landscape, weather evolution, and patterns in a period of 120 hours as if they themselves were a thousand miles tall. Wind activity can be observed by injecting particles that follow north-south of east-west wind paths. Individual particles can be injected as well as a ribbon of connected particles. The wand interface is used to fly through the geography and land in desired locations for more detailed observations. Figure 5 shows the soil temperature, the land usage and the water vapor.

#### **3.9.2 Discussion**

This visualization has the same problem with handling large data sets as in the Cosmic Explorer. Our implementation used a 50 Mbyte file that contained seven of the 15 weather elements generated by the simulation. We would need about 200 Mbytes of RAM to display a complete data set of regional weather data. One accomplishment of this application was the transformation of meteorologists into giants allowing them to walk large geographical areas with a single step inside the CAVE. They were absolutely thrilled by this new way of interacting with their data. Future work will involve the development of techniques to analyze climate simulations.

### **3.10 Realistic Modeling of Brain Structures with Remote Interaction Between Simulations of an Inferior Olivary Neuron and a Cerebellar Purkinje Cell**

**Collaborators:** James M. Bower, Erik De Schutter, Maurice Lee, Upinda Bhalla (California Institute of

Technology), Jason Leigh, Thomas A. DeFanti (University of Illinois at Chicago).

In recent years the greater availability of workstations has resulted in significant increases in modeling in many scientific disciplines. Modeling is attractive because it provides a deeper understanding of what is still unknown about the system, and thus helps us to guide our experiments so that we avoid generating massive amounts of unconnected data. Our CAVE application modeled two neurons (the Purkinje and the Inferior Olivary Neuron) in the cerebellum. Up until now, modeling of single neurons and neural networks has been relegated to single workstations or parallel computers. Our work involved simulating the interaction between, and visualization of two neurons at geographically distant locations, computed on heterogeneous computer systems. At Caltech, the Intel Touchstone DELTA simulated a cerebellar Purkinje cell, while in Chicago, a Sun Sparc station simulated an Inferior Olivary neuron. The two neurons were connected via a T3 line through Argonne National Laboratory, and all data generated during the interaction was simultaneously visualized on a Silicon Graphics Crimson on the exhibit floor of SIGGRAPH'92, in Chicago [4].

### 3.10.1 CAVE Visualization

At EVL, we provided a similar networking model, but the data was visualized in the CAVE rather than on a single workstation. The Sparc station used GENESIS (General Network Simulation System) to model the behavior of the Olivary neuron, and the Delta ran a parallel version of the same system to simulate the Purkinje cell. Additional networking components were added to GENESIS to allow communications over the Internet. All computed data were converted to RGB triples and sent, by both machines, to the CAVE for mapping over three-dimensional models of the two neurons. With the use of the wand, the user was able to inject a current into the soma of the Olivary neuron by touching it. This initiated an action potential in the neuron that in turn sent a triggering binary signal over the T3 line (acting as a climbing fiber synapse) to the Purkinje cell. The signal then initiated a complex spike in the Purkinje cell.

### 3.10.2 Discussion

Our first attempt at visualizing these results showed that we were immediately biased towards viewing the two neurons from an outside-in perspective. This was done primarily to allow the user to first become accustomed to the morphology of the neuron as a whole before allowing them to walk into the structure. The visualization offered computational neural scientists the first fully immersive visualization of the two neurons at simulated magnifications of over 100,000 times. We are currently working on more elaborate interactions between multiple neurons in the CAVE. In the future we plan to devise new

approaches for visualizing the enormous amounts of data generated from complex neuronal network simulations.

## 3.11 Visualization of the Molecular Dynamics of Cancer

**Collaborators:** Paul Bash (Argonne National Laboratory), Carolina Cruz-Neira (University of Illinois at Chicago).

In this application, molecular dynamics simulations are used to observe the behavior of the p21, an oncogene product protein that regulates the growth of cells by its interaction with the molecule guanosine triphosphate (GTP). The study of this protein is particularly relevant because changes in its molecular structure can lead to uncontrolled cellular growth and cancer. This application shows the motions and interactions of the atoms of the p21, its GTP substrate, and water molecules in the vicinity of the protein's primary site of action.

### 3.11.1 CAVE Visualization

The molecular dynamics simulation for the p21 protein was precalculated on a 16-IBM RS/6000 cluster for a period of 12 picoseconds of its lifetime. The simulation output data was used in the CAVE to recreate the molecules and their behaviors. The p21, the GTP and the water molecules bring over 2000 atoms and more than 4000 connectivity segments to the visualization. This seriously compromised the rendering speed. We informally discovered that rendering speeds under 8 frames per second reduced the immersive experience to a slide show. Hence, to keep within the acceptable speed limits, we simplified the molecular representation by using tetrahedrons for the atoms and simple antialiased lines for the connectivity. A color interpolation algorithm was used to simulate a lighting model. In the CAVE visualization, viewers can explore the molecule by holding it in their hands, translating and rotating it. The viewer can look at the whole simulation with all the molecules and atoms in wireframe mode or can select parts of the p21 molecule to increase the level of detail for a more thorough observation of that particular section. Figure 6 shows the main chain in the p21 molecule with some of its parts expanded displaying the atoms. Sound was used to identify the state of the molecules and to provide feedback when a section of the p21 molecule was selected.

### 3.11.2 Discussion

Dr. Paul Bash commented that his experience in the CAVE inspired a long list of future experiments he would like to develop in this environment. His enthusiasm gave us good indication that we had accomplished our initial goal of creating a useful and engaging environment for scientific research. We are currently working with Paul Bash on a more elaborate simulation that includes the connection of the CAVE to a supercomputer to calculate

the molecular dynamics in real time. The goal is to interactively modify the molecular structure of the p21 protein and observe the impact of the change. The CAVE provides a good environment for this type of research because it allows us to treat the molecule almost like a real object, with the advantage of having the real time computed behavior of the model. Another important contribution of the CAVE to this application is to enable several scientists to share the space; they can observe how one of their colleagues performs the manipulation, suggest changes or take over the manipulation.

#### 4 Conclusions and Future Work

These first user interactions have given us great insight into possible directions in VR and have revealed a number of inadequacies of the CAVE and VR systems in general. Viewing the data from the inside-out was a paradigm that few applications fully applied. Used appropriately, this can give a strong sense of immersion and participation in the environment; instead most applications chose to view their data from a distance, like on a workstation screen. As the scientists become more familiar with interacting in virtual environments, it is expected that they will make greater use of the inside-out paradigm, where appropriate.

It was discovered quickly that the memory limitations of the CAVE severely constrained the amount of data that could be visualized at one time. Computational scientific applications tend to generate enormous amounts of data, much of which may not be required by the visualization. It would be useful if the CAVE became a means for the user to intuitively filter out extraneous data. An immediate solution to this problem would be to increase the physical memory size of the system, or redesign applications to allow iterating through subsets of the data.

The logical consequence of being able to visualize large amounts of data in the CAVE was the need to compute this data concurrently and in real-time. Since most of the visualizations already made full use of the CAVE's processing capabilities, there was little left for any real-time, concurrent simulation. A solution, created for the neuronal simulation, was to delegate the computationally intensive simulation to external computers and transmit the computed data over high-speed networks to the CAVE for viewing. We are currently working on more efficient means of realizing this heterogeneous computing paradigm. In addition we are proposing a CAVE-to-CAVE link that will allow interactions between CAVE users at remote sites.

Improvements in the user-interface, in terms of both hardware and software, were found to be greatly needed. The wand is a simple device, allowing the user to press one of three buttons at a time, but the physical structure of the wand was not such that chord inputs were possible. In addition the CAVE did not provide any high level interface coding-routines that allowed users to easily manipulate their data. This tended to result in most of the interaction using only simple wand movements and button

presses. There was little attempt to make selections in space to trigger actions; such interactions typically required greater coding effort. We are now developing a comprehensive set of interface routines to encourage users to build more interactive applications. Proposed experiments will examine the processing of auditory and visual information by the user to understand how the addition of sound in an environment can affect human orientation and navigation.

#### 5 Acknowledgments

We would like to thank all the collaborating scientists and artists for assisting us in importing their research applications into the CAVE. Very special thanks also go to Gary Lindahl for technical support and Maxine Brown for her help and encouragement in the production of this paper. The material presented in this paper is based upon work supported by the National Science Foundation under Grant No. ASC-92138 and Argonne National Laboratory.

#### 6 Bibliography

- [1] Cohen, S.M., Multi-Dimensional Data Visualization Using the Parallel Coordinate Geometry. *Masters Thesis, University of Illinois at Chicago*, March 1993.
- [2] Cruz-Neira, C., Sandin, D.J., and DeFanti, T.A., Surround-Screen Projection-Based Virtual Reality. To be published in the *SIGGRAPH '93 Proceedings*, Aug. 1993.
- [3] Hudson, R., Visualizing Three-Dimensional Strange Attractors, *Masters Thesis, University of Illinois at Chicago*, 1992.
- [4] Leigh, J., E. De Schutter, M. Lee, J. M. Bower, T. A. DeFanti. Realistic Modeling of Brain Structures with Remote Interaction Between Simulations of an Inferior Olivary Neuron and a Cerebellar Purkinje Cell. *Proceedings of the Society for Computer Simulations: Simulations Multiconference*, Arlington, Virginia, Mar. 29, 1993.
- [5] Pletinckx, D., Quaternion calculus as a basic tool in computer graphics, *The Visual Computer*, 5, pp. 2-13, 1989.

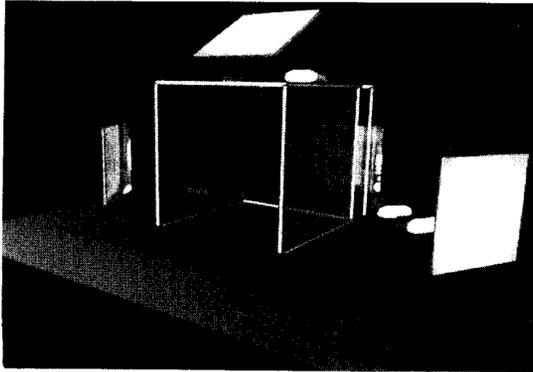


Figure 1: The CAVE audio visual experience automatic virtual environment.

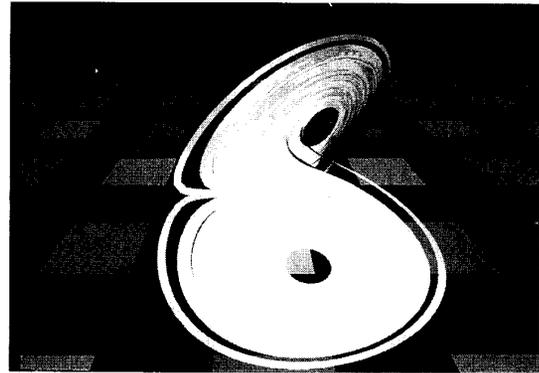


Figure 2: A mathematically derived surface model of the Lorenz attractor.

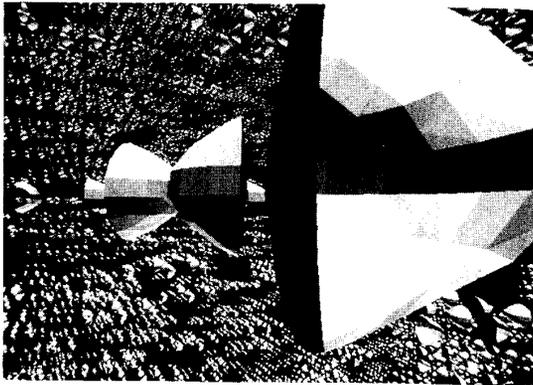


Figure 3: Successive refinement technique applied to the replication of superconductor cells.

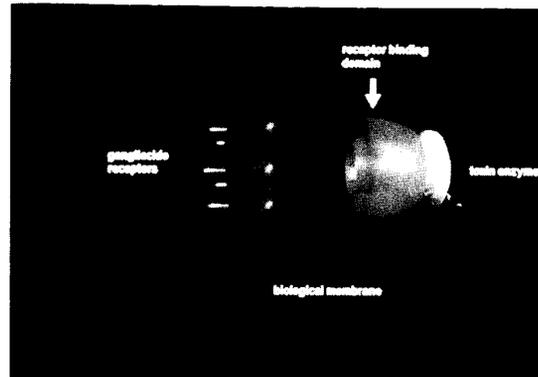


Figure 4: Cholera toxin invading its host cell.



Figure 5: Visualization of soil temperature, land usage, and water vapor in the virtual weather model.

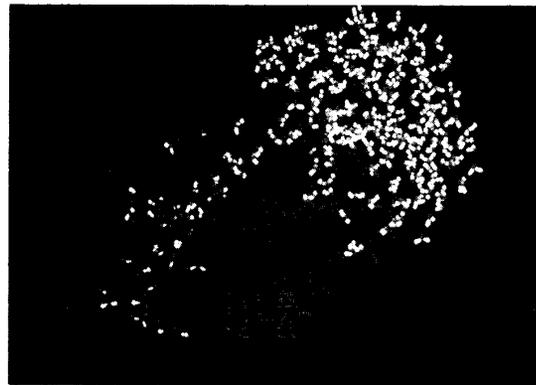


Figure 6: Visualization of the p21 showing the main chain in the molecule.

(See color plates, p. CP-2.)