The Cosmic Worm

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Sometimes scientists would like to stick their heads into interesting parts of their data sets and look around, but they are hampered by the "outside-looking-in" aspect of workstation-based visualization. At the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago, we are attempting to break some of the visualization barriers with a distributed computing and visualization environment developed using the Cave Automatic Virtual Environment (CAVE) virtual reality theater. In particular, we're trying to provide physicists and astrophysicists at the National Center for Supercomputing Applications (NCSA) a new vehicle for scientific discovery.

About the Worm

Our interest in visualizing astrophysical phenomena, combined with the NCSA scientists' need for new visualization techniques, resulted in our collaboration with NCSA's astrophysics and relativity groups. This unique combination of researchers has enabled the development of a CAVE-based visualization package that aids scientists in both camps. We dubbed this package Worm, after the theoretical stellar object called a wormhole.

Worm has two modes of operation: archive and real time. *Archive* mode plays back data from a simulation run at some previous time and stored to disk. *Real-time* mode lets the researcher control the simulation running live on a remote supercomputer such as the Connection Machine 5 (CM-5).

During Worm's real-time mode, the CAVE and CM-5 communicate with a unique configuration of hardware and software. The hardware connects over HiPPI/FDDI lines. The Data Transfer Mechanism (DTM) library developed at NCSA allows programmers at both ends of the link to treat communications as file-stream I/O, hiding the conversion and network protocol intricacies. Using DTM, Worm responds to CAVE user input, such as "pause the simulation," by sending control messages to the simulation. The simulation processes and responds to the incoming message, again using DTM. The same method transfers the 3D data volumes generated by the CM-5 simulation to Worm for visualization.

How the CAVE works

The CAVE is an immersive virtual environment, much like a small theater,[1] under development at EVL. It is a 10 × 10 × 9 foot cube, with images rear-projected on two to three walls and front-projected onto the floor. High-end Silicon Graphics workstations generate left- and right-eye images which users view through Stereographics' LCD shutter glasses. The head position and orientation of one participant, referred to as the driver, is tracked via Polhemus or Ascension electromagnetic sensors to give the correct visual perspective. A wand device, controlled by the main participant, provides one level of input through three buttons on its side, much like a 3D mouse. Unlike a mouse, the wand returns pitch, yaw, and roll as well as (x, y, z) position.

By wearing the shutter glasses, several other people can participate in the VR experience, viewing the CAVE from the driver's perspective. This provides an advantage over other VR systems, in that one scientist can view data while sharing the experience easily with colleagues.

Using a menu system, scientists can pause the simulation to analyze their data, restart the simulation with new parameters or variables, or continue the simulation to view the ongoing evolution of the physical parameters. Users can also interact with the data, navigate through the volume, step through time steps, or select a subvolume of data to visualize (Figure 1).

Figure 1a shows the selection of a subvolume in progress during a Worm visualization. The red box within the

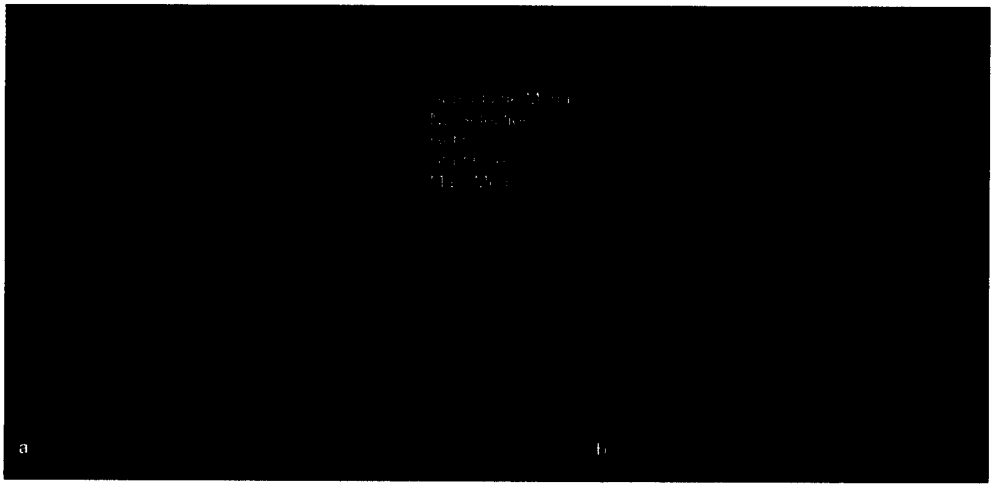

Figure 1. Using Worm, a scientist can invoke a number of menu options during a visualization. (a) The red box indicates the selected subvolume. (b) The results of performing the subvoluming menu option.

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Figure 2. Two density isosurfaces representing gas distribution since the Big Bang. The opaque white surface is denser than the semitransparent purple surface.

volume of data outlines the chosen subvolume. The scientist then invokes the subvoluming, using the menu shown to the right of the data cube. Figure 1b shows the resulting data subvolume.

The science

Working with the NCSA's astrophysics and relativity groups, we are visualizing different phenomena with Worm, including early universe formation, fluid flow, and gravitational waves.

Astrophysics

The understanding of many astrophysical phenomena relies upon the physics of fluid flow coupled with gravity. For example, simulations of early universe formation represent the evolution of gas density in the universe since the time of the Big Bang. Immediately after the Big Bang (approximately 15 billion years ago), gas distribution in the universe was nearly homogenous. As time progressed, the gas fragmented and collapsed under its own gravity. Following the evolution of density isosurfaces shows that the amount of gas at high density within the surfaces increases with time. At the end of the simulation, the density distribution looks similar to that seen in observational surveys. Figure 2 shows two density isosurfaces from the end of the simulation. The light, opaque surface is denser than the purple, semitransparent surface.

Rayleigh-Taylor instability simulations show what happens when a heavier fluid lies on top of a lighter fluid. Gravity makes the heavier liquid form fluid fingers that flow down into the lighter liquid, causing mixing and turbulence. Each surface in Figure 3 represents a different stage of the interaction between the two fluids. The light, opaque surface is the earliest stage. The light blue, semitransparent surface is beginning to show finger formation a few time-steps later. Many astrophysical objects behave this way, such as the remnants of supernovas and the atmospheres of some stars.[2]

Relativity

Theoretical studies of gravitational waves are important to physicists, because we only have indirect evidence of their existence. Einstein's theory of gravity, known as General Relativity, predicts gravitational waves, but as of this writing no device has measured them directly. They should be generated by violent cosmic events, such as the supernova explosion of a massive star or the collision of two black holes.

The Ligo (Laser Interferometer Gravitational Wave Observatory) and Virgo projects[3] will construct highly sensitive devices to try to measure gravitational radiation. Visualizations like those produced by Worm (Figure 4) should give scientists a better understanding of

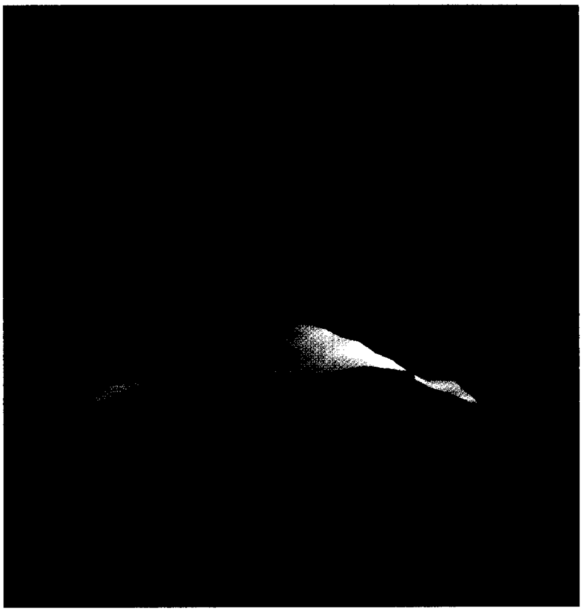

Figure 3. This Rayleigh-Taylor instability simulation shows the interaction as a heavy liquid settles into a lighter fluid over time, forming fluid fingers.

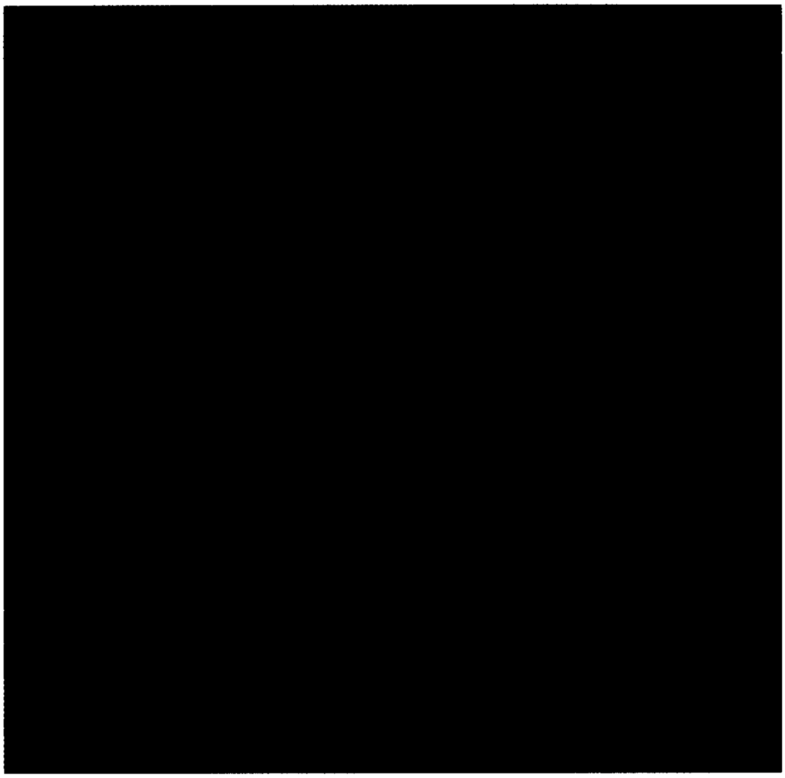

Figure 4. A visualization of a single gravitational wave component.

gravitational waves, helping them develop accurate numerical codes to simulate the cosmic events that should produce gravitational waves. Such studies will tell scientists what to look for when the gravitational wave detectors come on line and start collecting data.

As a research tool

Scientists already realize Worm's potential as a research tool. Even in the early developing and testing stages, they discovered things about their data they'd never seen before. Greg Bryan, a member of the astrophysics group, found that not only did his simulation produce the expected filaments of high-density gas, but the filaments actually move through space, a phenomenon not apparent in his workstation visualizations. Ed Seidel, head of the gravitational group, feels that Worm gives an improved, unique perspective on the data, while offering intuitive control. Bryan agreed, saying, "This is the first time we've been able to do interactive three-dimensional simulations."

Still going

"There is so much data that the standard visualization paradigm is inadequate," said Seidel. The amount of data these simulations generate is often in the range of tens or hundreds of megabytes, and can run into terabytes. Our combination of virtual reality and supercomputing opens the door to interactive visualization of this data. Even so, at this stage we can only handle the smallest of volumes, on the order of 32^3 ($32 \times 32 \times 32$) voxels. The size of the data set affects every step of the visualization: the data transfer from a local disk or the CM-5 to the CAVE, the isosurface rendering time, the number of polygons per frame, and the frame rate. As we improve our algorithms and increase the data computation and network transfer rates, we would like to visualize volumes upwards of 256^3 or 512^3.

The current version of Worm is a prototype showcased in the CAVE at last November's Supercomputing 93 in Portland, Oregon. We are continuing the work with NCSA, planning several improvements and additions for implementation over the next few months. The next revision of Worm will appear in the VRoom event at Siggraph 94 in July. NCSA recently built a CAVE at their facility, a major step toward our ultimate goal of providing an interactive virtual reality research tool the scientists can use on a daily basis. ❑

Acknowledgments

We would like to thank Tom DeFanti for access to superior computing environments. We would like to thank our NCSA scientists Ed Seidel, Joan Masso, Mike Norman, and Greg Bryan for their invaluable and ongoing support for this project, and Dan Weber and Jeff Terstriep for their networking expertise. Finally, our thanks to Maxine Brown for her continual encouragement and feedback.

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Note: Readers can obtain additional information on this and related projects at EVL and NCSA online via Mosaic or by contacting the authors at {trina, goldman}@evl.eecs.uic.edu. EVL's home page is at Mosaic URL address http://www.ncsa.uiuc.edu/EVL/docs/Welcome.html. The Mosaic URL address for NCSA's Applications Group is http://www.ncsa.uiuc.edu/Apps/AppsIntro.html.

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