Visualizing Large, Heterogeneous Data in Hybrid-Reality Environments

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Hybrid-reality environments blur the line between traditional virtual environments and tiled display walls. They incorporate high-resolution, stereoscopic displays and can be used to juxtapose a variety of datasets while providing a range of naturalistic interaction schemes. They thus empower designers to construct integrative visualizations that more effectively mash up 2D, 3D, temporal, and multivariate datasets.

Vision is our dominant sense, with roughly a quarter of our brain devoted to processing visual stimuli, providing the highest-bandwidth perceptual channel into our cognitive systems. This advanced neural circuitry, shaped by millions of years of evolution, lets us recognize recurring patterns, quickly attend to the unexpected, and visually solve complex spatial and abstract problems. It's no surprise that early optical instruments were central to many scientific breakthroughs, from Anton van Leeuwenhoek's discovery of living cells in 1674 using a self-built microscope to Pierre Janssen and Norman Lockyer's discovery of helium in 1868 via direct observation of solar prominences with a telescope.

Much of the data scientists investigate today is digitally created, stored, and analyzed. Scientists are observing phenomena with new types of digital instruments, sensors, and robotic exploration vehicles that can collect data at ever-increasing resolutions. Although this trove of modern digital data isn't directly amenable to visual observation with traditional optical lenses, visualization lets us transform this data into visual representations.

However, despite many recent advances, the scale, heterogeneity, and complexity of modern scientific datasets continue to pose major challenges for visualization designers. In many situations, there are just too few pixels to effectively visualize these datasets. Moreover, solving scientific problems today requires concentrated effort from interdisciplinary teams who deal with various data sources, including 3D, 2D, abstract, temporal, and multidimensional datasets. It's challenging to construct integrative visualizations that can simultaneously and effectively cater to such a variety of data sources.

Just as Leeuwenhoek invented his own lens to look at his water samples four centuries ago, scientists are constructing new types of digital lenses—high-resolution computer displays that can effectively be used to visualize large amounts of data. Many scientific disciplines are rapidly adopting modern digital lenses such as the Cyber-Commons and CAVE2, both from the Electronic Visualization Laboratory at the University of Illinois at Chicago. (CAVE stands for Cave Automatic Virtual Environment.) These big lenses let scientists

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- visualize and juxtapose multiple interrelated datasets to find insights between previously disparate pieces of information,[1]
- dedicate more effort to analysis by reducing window switching,[2] and
- significantly increase the amount of data that can be viewed at one time.[3]

(For further information on the Cyber-Commons and CAVE2, see the "Realizing Hybrid-Reality Environments with Commercial 3D Technology" sidebar.)

Like modern binocular microscopes, the Cyber-Commons and CAVE2 provide high-resolution, stereoscopic display surfaces, creating *hybrid-reality* (HR) spaces that blur the line between virtual environments and tiled display walls. With their unique characteristics, HR environments empower designers to construct scalable, integrative visualizations that mash up 2D, 3D, temporal, and multivariate data sources. This in turn will allow a new generation of applications better suited to meet the challenges of making sense of today's increasingly large and heterogeneous datasets.

Realizing Hybrid-Reality Environments with Commercial 3D Technology

The Cyber-Commons and CAVE2 (CAVE stands for Cave Automatic Virtual Environment) are hybrid-reality environments employing commercial thin-bezel, stereo-capable LCD panels. The Cyber-Commons comprises 18 panels on a wall with 19-Mpixel resolution. CAVE2 comprises 72 panels (18 columns by 4 rows) arranged on a 24-foot-diameter cylinder with a total resolution of 72 Mpixels (36-Mpixel stereo resolution), providing 20/20 visual acuity from its center.

Both displays use micropolarization technology for stereoscopic depth. A micropolarizer is a thin (0.8 mm) overlay that polarizes each pixel row in alternate directions, providing cost-effective two-channel separation. To reduce channel cross-talk, the micropolarizer array for the top- and bottom-most panels in CAVE2 have been shifted down and up, respectively. This reduces ghosting, which results from off-axis viewing of the outer-edge panels.[1] To support correct stereoscopic viewing by multiple individuals simultaneously, CAVE2 can also operate in panoptic-stereo mode. In this mode, the system normalizes the horizontal stereo disparity so that it's parallel to each panel's surface.

Reference

1. A. Febretti et al., "CAVE2: A Next-Generation Hybrid Environment for Immersive Simulation and Information Analysis," *Proc. IS&T/SPIE Electronic Imaging*, vol. 8649, Int'l Soc. for Optics and Photonics, 2013.

The Evolution of Large-Scale Visualization Environments

Traditional LCD desktop and laptop monitors are pervasive, inexpensive, and of relatively moderate resolution. Most LCD displays have a maximum resolution of 4 Mpixels, which is insufficient to visualize big or multiple datasets at their native resolution. Consequently, these displays force visualization designers to make trade-offs to render more information. The trade-offs, however, often place an additional cognitive burden on the user, potentially hindering complex analysis tasks. For example, when users navigate large datasets by panning or zooming and switching between multiple windows, they could be distracted from the task at hand when they're forced to consciously perform such nonessential interactions.[2] Traditional desktop monitors are therefore poorly suited for complex analysis scenarios that involve the integration of large amounts of data.

Scientists in Wonderland

The CAVE's invention in 1992 was a defining moment for VR that had ramifications for scientific visualization. The first CAVE was a hollow 10-foot cube, with interactive computer graphics projected on four of its surfaces, providing 5 Mpixels of aggregate resolution (which was very high at the time). Its ability to immerse users with stereoscopic graphics made it attractive for exploring 3D data such as molecules, astrophysical phenomena, and geoscience datasets.[4]

Although the original CAVE provided limited resolution and a poor contrast ratio, modern descendants with high-end projectors have greatly improved the picture quality. However, the CAVE's reliance on projectors and its enclosed nature have limited its use to purposely built, dimly lit spaces, making them difficult to integrate in office environments. This has hindered their adoption in everyday scientific workflows and limited them to opportunistic use.

Large, High-Resolution Display Walls

More recently, large display walls have emerged as a platform for large-scale data visualization.[5] Constructed by tiling LCD monitors to form a contiguous surface, these ultra-high-resolution displays let scientists juxtapose a variety of datasets for analysis and correlation. Knowledge workers and scientists have successfully integrated large display walls into their everyday workflows. Compared to CAVEs, tiled LCD walls provide superior image quality and resolution—up to 1,000 Mpixels. The monitors can be easily calibrated (with far less effort than projector-based systems), improving visualizations by providing consistent color and luminance across the display surface.

Traditional CAVEs and large display walls have distinct qualities that make them effective for visualizing different classes of data. CAVEs are extremely effective for 3D spatial datasets but are far less suited for 2D information visualization. Tiled display walls excel at visualizing large 2D, abstract, multivariate datasets. However, they're less suited for 3D data because they don't provide the same degree of immersion and often can't utilize stereoscopy. So, we wanted to merge traditional CAVEs and large display walls to leverage both technologies' strengths.

The main features of hybrid-reality environments are a superset of the characteristics of traditional immersive VR systems and large display walls.

A Hybrid 2D-3D Approach to Visualization

LCD display technology is advancing rapidly while its cost is decreasing. Thin-bezel LCD panels are becoming more common, and several manufacturers have introduced thin-bezel panels with built-in support for stereoscopic 3D. This accelerating trend presents the opportunity to build HR environments, which combine the benefits of immersive VR and traditional tiled display wall environments. HR environments have five main characteristics:

- A large, high-resolution display with a high pixel density. The resolution should come close to matching human visual acuity.
- Support for stereoscopic depth. The benefits of stereoscopy aren't limited to 3D datasets. As we'll show, 2D representations can also benefit from stereoscopic depth.[6,7]
- Support for naturalistic interactions. These interactions could include keyboard and mouse, six-degree-of-freedom joysticks, head tracking for a viewer-centered perspective, and voice-activated interfaces. The appropriate configuration is, of course, application dependent.
- A space to encourage multiple colocated individuals to collaborate. The ability to solve complex problems involving big data often requires a variety of scientific expertise. So, HR environments should provide an inviting space where scientists from different disciplines can comfortably sit together to analyze and interpret data.
- A software layer that leverages the hardware to simultaneously display multiple related datasets and utilize hybrid 2D-3D visualization and interaction modalities.

These characteristics synergize capabilities of VR and high-resolution tiled displays, giving rise to a qualitatively distinct visualization environment that combines the best of both worlds. The fusion of these two formerly separate modalities results in environments that are capable of rendering large volumes of data while simultaneously catering to the visualization and interaction requirements of different data classes. So, how can we draw on these capabilities to realize better, more scalable visualizations?

Improving Visualization's Scalability with HR Environments

The main features of HR environments are a superset of the characteristics of traditional immersive VR systems and large display walls. Designers can leverage these features to improve visualization scalability in big-data scenarios.

Stereoscopic Depth

A main challenge in big-data visualization is avoiding visual clutter. The sheer number of data points often makes visualizations too dense to be useful. Cluttered visualizations increase the cognitive workflow of users, making it difficult to read variables, compare elements, or recognize trends in the data.

A 2D display exacerbates clutter by forcing designers to pack all the elements on a single 2D plane. This reduction of visual dimensionality, which discards our visual system's natural ability to perceive and interpret 3D spaces, is potentially harmful to the scalability of visualizations.

A 3D display, on the other hand, allows designers the freedom of layering information in 3D to reduce clutter and potentially improve comprehension and performance. However, although stereo-capable displays are available in the form of commercial monitors and existing VR systems, most of these provide a limited resolution that's significantly below the acuity of our visual system.

HR environments' improved stereoscopic resolution is crucial in letting viewers utilize depth perception when reasoning about big datasets. For example, using a high-resolution display that matches our visual acuity, we could increase the data size tenfold in graph comprehension tasks by rendering node-link diagrams in stereoscopic 3D with motion parallax cues.[7] (For comparison,

Figure 1. Students having an immersive meeting in CAVE2. The space can comfortably accommodate from five to seven individuals with chairs and tables. CAVE2 can be used to effectively juxtapose 2D, 3D, and abstract data, as well as text documents. It features a 320-degree panoramic view at 20/20 visual acuity. With a total of 72 thin-bezel, stereoscopic LCD panels, it has 10 times the resolution of the original CAVE at half the cost.

a similar experiment yielded a threefold improvement at best when using a moderate-resolution stereo display.[8])

Immersion

There's solid empirical evidence backing the benefit of immersion in data exploration and analysis scenarios.[9] One of HR environments' main contributions is transforming traditional tiled display walls into highly immersive systems, incorporating head tracking, six-degree-of-freedom input devices, and in some cases a panoramic field of view. In particular, head tracking coupled with motion parallax cues helps us understand spatial relationships by leveraging our natural capacity for spatial cognition. This ultimately enhances user performance in visual data analysis tasks and improves visualization's scalability.[7,8]

Room for Physical Navigation and Collaboration

Traditional VR environments tend to be enclosed and somewhat isolating. HR environments, on the other hand, provide large and open spaces, allowing for a greater degree of physical navigation, such as walking up to the display surface to see details. Embodied navigation is superior to virtual navigation, particularly when dealing with large data volumes.[3,10]

HR environments are also more suitable for collaboration than traditional CAVEs, which can fit only a few standing individuals. In contrast, up to 15 individuals can comfortably stand in CAVE2. HR environments can also be incorporated into traditional office spaces, making them more suitable for long-term use. The CAVE2 space, for instance, can be configured as an immersive meeting room (see Figure 1). Using LCD displays instead of projectors also results in cooler, quieter, and more comfortable work spaces.

Different Strokes for Different Folks

To appreciate how designers can leverage the unique affordances of HR environments to realize different visualization experiences, we first look at new modes of operation that HR environments intrinsically support. You can think of them as design patterns that could be instantiated into applications.

Hybrid 2D-3D Visualizations

Scientific projects increasingly require the integrated analysis of large, multivariate, heterogeneous datasets. Scientists often need to examine and compare multiple interrelated visualizations to uncover hidden relationships and gain insights. For instance, geoscientists studying ice-covered lakes want to look at 3D bathymetries alongside 2D scatterplots and charts depicting chemical properties in the water column. Patterns found in the 2D graphs must be correlated with topographical features in the 3D model, and vice versa.

HR environments can greatly facilitate such integrative analysis by providing visualization capabilities suited for a wide range of data classes. With stereoscopic depth, 3D data can be presented more effectively to improve spatial understanding of complex structures. On the same display surface, we can also juxtapose large multivariate datasets in multiple views (in scatterplot matrices, for instance).

We are collaborating with domain scientists to develop and evaluate hybrid-reality visualizations within the context of real-world scientific investigations.

Besides supporting 2D and 3D representations, HR environments support different interaction modalities. For instance, a stereoscopic 3D view could employ a viewer-centered perspective by tracking the user's head. This could be coupled with a fly-through navigation metaphor using a wireless joystick for 3D translation and rotation. On the other hand, 2D scatterplots can benefit from traditional pointer-based interaction, letting users interactively query the data and cross-highlight interesting features.

2D Visualizations with Stereoscopic Depth Cues

Although stereoscopy has traditionally been the exclusive domain of 3D visualizations, 2D layouts can also benefit from it. Stereoscopy can serve as a supplementary perceptual channel in 2D visualizations, encoding additional information. For instance, we depict time in the third dimension using stereoscopic depth by rendering elements at varying depths.

Stereoscopy can also increase performance in common information visualization tasks. For example, we can speed up visual searches by drawing targets so that they lie on a different plane that's closer to the user.[6] This technique can be used to encode information that needs to pop up when other preattentive channels, such as color, are unavailable.

You could argue that stereoscopy in this context isn't a novel feature; traditional 3D desktop displays and TVs already provide the option to render stereoscopic content. However, with HR environments, we can leverage the high-resolution display surface to render big datasets that are orders of magnitude larger, compared to commercial 3D TVs and monitors. Indeed, we found that stereoscopic depth cues are effective on large tiled displays, letting viewers see depth-encoded features on a large-scale basis.[11]

Notably, stereoscopy here doesn't imply a 3D visualization in the traditional sense. HR environments can be thought of as large visualization canvases on which you can project 2D and 3D glyphs at arbitrary depths, creating pseudo-3D worlds where some elements float in 3D while others are rendered with zero stereo disparity to appear as purely 2D glyphs.

Fully Immersive 3D Visualizations

Thanks to HR environments' large size and stereoscopic 3D capabilities, they can serve as immersive virtual environments, enabling one or more users to be immersed in 3D visualizations. When head-tracked, users can experience a viewer-centered perspective, enabling them to use embodied interaction. For example, they can walk around a molecule or move their head to peek over a cliff. This lets scientists make sense of complex 3D datasets, giving them a better understanding of the spatial relationships and structures in those datasets.[4]

Although this mode is similar to what projection-based VR environments provide, HR environments are more suitable for visualizing big datasets. They typically provide better color and luminance consistency across display surfaces, improving color perception in visualizations that rely heavily on color coding. The enhanced contrast ratio and sharpness also allow for more complex 3D structures, particularly in volume-based visualizations.

Applications

We are collaborating with domain scientists to develop and evaluate HR visualizations within the context of real-world scientific investigations. The following four applications demonstrate HR environments' potential and how they can further the exploration and analysis of large scientific datasets.

The Endurance Project

The McMurdo Dry Valleys, in Victoria Land in Antarctica, constitute one of the world's most extreme deserts and are the largest snow-free region in the continent. Some lakes in the Dry Valleys

Figure 2. A visualization of Endurance (*E*nvironmentally *Nond*isturbing *U*nder-ice *R*obotic *An*tarctic *E*xplorer) datasets on the Cyber-Commons. The left side shows the stereoscopic 3D bathymetry of Lake Bonney, an ice-covered lake in the McMurdo Dry Valleys in Antarctica. The right side shows several 2D plots depicting chemical and biological variables in the water column.

rank among the world's most saline. One of them is Lake Bonney, a perennially ice-covered lake at the end of the Taylor Glacier. Because the Dry Valleys are one of the terrestrial environments most similar to Mars, they're an important source for insights into possible forms of extraterrestrial life.

So, NASA funded the Endurance (*E*nvironmentally *Nond*isturbing *U*nder-ice *R*obotic *An*tarctic *E*xplorer) project. Endurance was an autonomous underwater vehicle (AUV) designed to map Lake Bonney's geometry, geochemistry, and biology in 3D.

The AUV operated during the Antarctic summers of 2008 and 2009. Each mission entailed a set of AUV deployments, resulting in 45 dives. The AUV had three science objectives: bathymetry scanning, water chemistry profiling, and glacier exploration. For bathymetry reconstruction, the source data consisted of approximately 200 million distinct sonar range returns. From these sonar points, scientists generated a high-resolution 3D model of the lake bottom, comprising approximately 200,000 vertices and 400,000 faces.

To understand this extreme environment's chemical and biological features, the scientists needed to reference chemical and biological properties of the water column (about 50,000 samples) to their 3D points of collection. Furthermore, they needed to compare samples from different locations side-by-side and see how the chemical and biological properties change across areas of the lake.

To address these requirements, we designed a visualization tool that mixes 2D scatterplots of chemical properties in the water column and 3D views of the lake's bathymetry data. The visualization supported both standard laptop displays and HR environments. When the visualization was rendered on the Cyber-Commons, researchers could visualize the bathymetry in stereoscopic 3D to better capture the complex features of the glacier interface with the lake and to disambiguate sonde (water sensor) drop positions (see Figure 2).

The Cyber-Commons also let researchers visualize the 3D bathymetry model in high detail, eliminating the need for excessive virtual navigation such as zooming and panning, which occurred frequently when the visualization ran on a laptop display. Besides the 3D view, multiple highly detailed 2D scatterplots could be generated and viewed side-by-side.

We further improved data analysis by keeping all views linked. Users could perform brushing-and-linking operations on any of the 3D or 2D views, and the changes would be reflected across the visualization. For instance, picking sonde drop locations in the 3D map would highlight the parts of the 2D salinity and water temperature curves corresponding to those locations.

The actual quantitative values could also be brought up and highlighted in a spreadsheet, giving scientists the opportunity for precise quantitative chemical readings for locations of interest. This was very useful for verification because the

Figure 3. A visualization of ant trajectories on the Cyber-Commons in a 2D layout with stereoscopic depth cues. Trajectories were grouped into bins and collectively analyzed. The inset illustrates the coordinated brushing feature used to formulate and perform quick visual queries.

chemistry profiles influence the 3D reconstruction of the bathymetry from sonar pulses.

Ultimately, the visualization on the Cyber-Commons helped scientists develop a cohesive, high-level view of the various types of data collected by the AUV. This integrated visualization led to a better appreciation of the lake bottom's topography, coupled with an understanding of how chemical and life indicators change across the lake and in the water column.

Understanding Terrestrial Insects' Navigational Strategies

To understand animals' navigational strategies and decision-making processes, ecologists track and analyze their movement patterns. Thanks to modern tracking and sensor technologies, ecologists can survey animal movement at unprecedented spatial and temporal resolutions, giving them a richer understanding of the behavior.

However, this has led to increased amounts of data to analyze. One particularly challenging area is the study of insect behavior because the data entomologists collect pose many analytical problems. Insects typically exhibit stochastic, locally scoped movement patterns that are difficult to characterize case-by-case. To understand their behavior, ecologists resort to collecting a large sample of trajectories under varying conditions to tease out general responses.

The sheer number of trajectories collected during experimentation makes them extremely difficult to visualize on traditional displays. Although a laptop or desktop screen could simultaneously visualize a few trajectories, researchers would need to switch between different sets of trajectories to cover all the data. This makes it hard to perform a comparison across a large set of trajectories—a crucial task in this domain. Besides, owing to the many plausible hypotheses and explanations concerning an observed movement pattern, entomologists need a scalable, efficient way to explore these hypotheses. It's difficult, however, to formulate hypotheses and theories when looking at a few instances at a time. It's even more challenging to test whether the data actually supports those hypotheses.

We used the Cyber-Commons display to visualize large collections of insect movement data collected from video sequences (see Figure 3). The visualization employs a small-multiples layout to simultaneously show approximately 500 insect trajectories collected under various experimental conditions. This layout let the researcher divide the screen real estate into configurable bins to group related trajectories. For example, one bin might show trajectories of ants captured east of the colony's main foraging trail, whereas a second bin might contain ants captured on the trail while carrying a seed.

The visualization was used to study the movement patterns and navigational strategies of Kenyan seed-harvester ants. Although ant movement is naturally restricted to two dimensions, we used the Cyber-Commons' 3D capability to encode time. We rendered each trajectory in stereoscopic 3D. The *xy*-plane (the display surface) encoded an ant's movement; the *z*+ axis (away from the display) encoded time. To generate stereo-pair images, we applied a sheer transformation along the *x*-axis (negative sheer for the left-eye image and positive for the right), which produced an orthographic 3D projection that doesn't suffer from perspective distortion (see Figure 4). The trajectories appeared as cylinders sprouting toward the viewer.

Using stereoscopy to encode time made the ant movement's temporality visually evident. This was of paramount importance to the researcher, who was interested in understanding the insect's decision-making process over time. Because our data had high temporal resolution, with each trajectory containing 30 visual fixations per second, we utilized the expansive horizontal resolution of the Cyber-Commons display to depict the trajectories at a high temporal resolution. To do this, we exaggerated the stereo disparity by increasing the shear coefficient, which caused an increased divergence between the pair of stereo images. The increased divergence resulted in extra depth perception, which in turn revealed additional temporal details. To avoid excessive eyestrain, we provided a slider for the researcher to limit the maximum stereo disparity.

To let the researcher explore hypotheses regarding ant behavior and quickly determine whether the data supported them, we added two interactive tools. First, a coordinated brushing tool let the researcher brush the background of a single trajectory. This would cause the visualization to highlight in color all other trajectories whenever the insect moved over the brushed area. For example, the researcher could brush the west (left) side of the trajectory to highlight experiments in which the ant exited the arena from that side.

Second, a temporal filter let the researcher specify a time window. This caused the visualization to display trajectory segments corresponding to the specified time only, such as at the experiment's beginning.

Using these tools in concert, the researcher could translate a hypothesized spatiotemporal behavior pattern into a visual query and visually test whether the data confirmed or contradicted that behavior.[11] This let her quickly query the dataset and explore a large number of hypotheses in a scalable, intuitive manner. Thanks to the high-resolution display, she could visually query a large portion of the data in seconds. Stereoscopic 3D also proved crucial in revealing recurring movement patterns, which would have been difficult to detect otherwise. The researcher commented that the Cyber-Commons was the only way she could perceive insect behavior's temporality, not only for a single trajectory but also on a large scale.

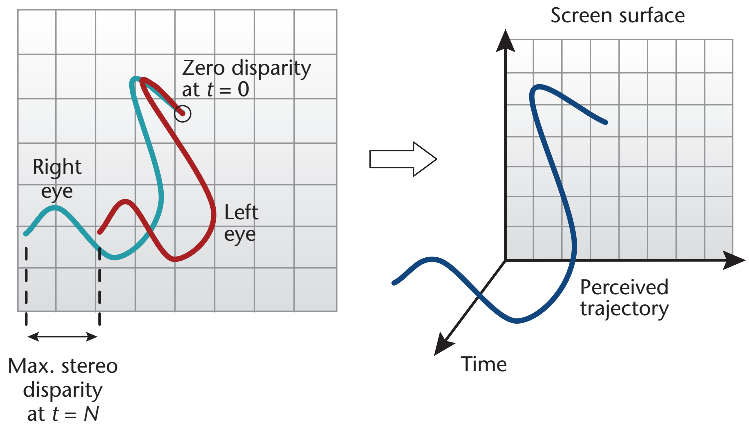

Figure 4. The visual encoding of an ant trajectory, with stereoscopic depth cues to convey time. We use an orthographic 3D projection to avoid perspective distortion.

Molecular Visualization for Nanoscale-Materials Science

To study nanoscale materials, scientists conduct large-scale molecular dynamics (MD) simulations to understand the diffusion and interactions between atoms at the nanometer level. For example, researchers at the University of Southern California's Collaboratory for Advanced Computing and Simulations routinely use Argonne National Laboratory's leadership computing resources (the most powerful of its supercomputers) to conduct simulations involving tens to hundreds of millions of atoms.

Materials scientists also use density functional theory (DFT) simulations, which generate charge density fields (3D scalar volumes representing the electron density around atoms). This lets them model electron behavior, giving them a better understanding of the subatomic structure.

The 3D nature of nanoscale molecules and charge density fields makes them ideal targets for immersive VR environments. With wireless interaction and head tracking, scientists can immerse themselves within these tiny structures and explore them by walking around the environment.

An important aspect of nanoscale-materials design is understanding the nature of surfaces and material interfaces. This is particularly important in energy storage and catalysis applications. At the nanoscale level, however, the notion of a surface becomes probabilistic. This makes geometric models, such as 3D meshes and isosurfaces, inappropriate for nanoscale surface representations because they don't visually convey this uncertainty.

To effectively render such data in real time, we employed Nanovol, a GPU volume ray-casting application for large atomistic data.[12] Rather than visualize molecular boundaries with discrete surfaces, we volume-render charge density clouds to

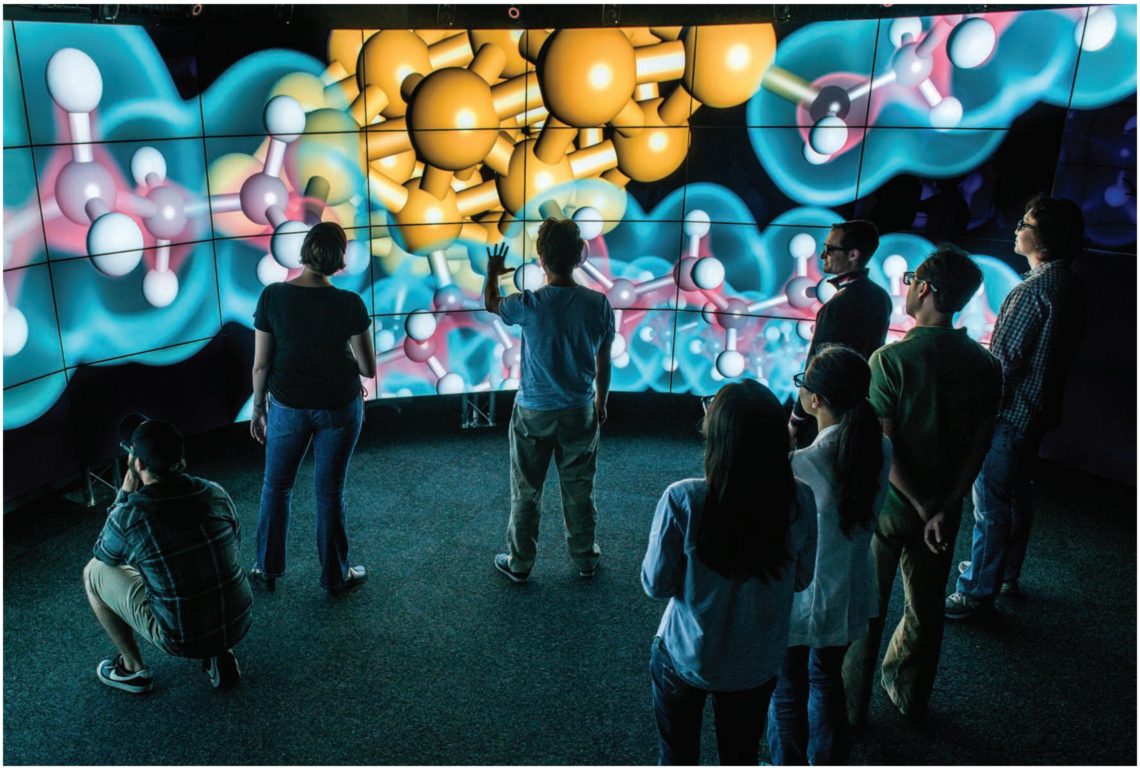

Figure 5. An immersive visualization of a density-functional-theory simulation in CAVE2. The visualization shows a ball-and-stick model of an octyne catalysis study. The clouds represent the probability density of electrons, with colors encoding electron orbitals. CAVE2 lets us accurately render and resolve volumetric clouds in stereoscopic 3D.

convey the uncertainty in the definition of surfaces at the nanoscale.

However, this approach introduces a challenge in older projection-based VR environments, which don't have enough contrast and resolution to effectively display and resolve cloud-based volumetric representations. Furthermore, getting a consistent coloring and luminance across all projected surfaces is difficult. This hinders perception of charge density clouds, making it difficult for materials scientists to correctly interpret electron orbitals and bonds between atoms.

Using HR environments, on the other hand, we can effectively visualize DFT simulations in stereoscopic 3D in a scalable and perceivable manner. Figure 5 illustrates a visualization of a DFT simulation of a catalysis study in CAVE2.

For MD simulations, which don't produce charge density fields, we developed an approximation model to generate an artificial 3D charge density field from atoms' positions. This also aids with the visualization of large-scale MD simulations comprising millions of atoms by reducing clutter and emphasizing large-scale structural features.

Figure 6 shows a CAVE2 MD simulation of a glass fissure, comprising approximately five million atoms. The green clouds represent the approximate charge density field, which serves as a natural way to reduce clutter in the visualization, improving its scalability. A viewer-centered perspective with stereoscopic rendering lets users walk in the space and explore the dataset or use a wireless wand to move or rotate the structure.

The ability to visualize 3D datasets in immersive VR environments is well established. Compared to traditional VR platforms, HR environments significantly improve image quality and resolution, enhancing perception of large-scale 3D datasets. Moreover, with LCD-based HR environments, we can now visualize and resolve far more complex visual representations, such as clouds and volumes.

Toward 1000 Genomes Visualization

With genome-sequencing costs decreasing more quickly than Moore's law, researchers are generating massive amounts of genomic data to help solve diverse sets of problems in biology, health, and sustainable agriculture. For instance, the 1000 Genomes Project (www.1000genomes.org) gives researchers the opportunity to identify genetic variations that can be linked to cancers and other serious disorders such as Parkinson's disease.

Genomic researchers thus face new opportunities along with big-data challenges. In light of this, new genome visualizations are needed to enable scientists to compare and analyze not just dozens but

Figure 6. A real-time immersive visualization of a molecular-dynamics simulation of a glass fissure, comprising approximately five million atoms. CAVE2's high resolution allows such massive nanoscale structures to be resolved in stereoscopic 3D.

hundreds or even thousands of sequenced genomes. To help realize this goal, we're developing genome visualizations for HR environments in collaboration with genomic researchers.

HR environments allow for a new type of high-density genome visualization, making it possible to view genomic data from hundreds to thousands of genomes in a single view. Stereoscopic depth cues could highlight genomic elements of interest or encode sequence-level similarity by layering elements at different depths. Furthermore, HR environments will allow the juxtaposition of other data types, such as 3D protein structures in stereo, alongside 2D representations of genomic sequences.

HR environments have great potential in helping us tackle some of the complex visualization challenges involving large amounts of heterogeneous information. We will continue to work with domain scientists to explore and evaluate other application areas. We are also working on characterizing the design space for HR environments to provide guidelines for visualization designers.

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References

1. C. Andrews, A. Endert, and C. North, "Space to Think: Large High-Resolution Displays for Sensemaking," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 10), ACM, 2010, pp. 55–64.
2. R. Ball and C. North, "Effects of Tiled High-Resolution Displays on Basic Visualization and Navigation Tasks," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 05), 2005, ACM, pp. 1196–1199.
3. B. Yost, Y. Haciahmetoglu, and C. North, "Beyond Visual Acuity: The Perceptual Scalability of Information Visualizations for Large Displays," *Proc.*

SIGCHI Conf. Human Factors in Computing Systems (CHI 07), ACM, 2007, pp. 101–110.
4. C. Cruz et al., “Scientists in Wonderland: A Report on Visualization Applications in the CAVE Virtual Reality Environment,” *Proc. IEEE Symp. Research Frontiers in Virtual Reality*, IEEE, 1993, pp. 59–66.
5. J. Leigh et al., “Scalable Resolution Display Walls,” *Proc. IEEE*, vol. 101, no. 1, 2012, pp. 115–129.
6. B. Alper et al., “Stereoscopic Highlighting: 2D Graph Visualization on Stereo Displays,” *IEEE Trans. Visualization and Computer Graphics*, vol. 17, no. 12, 2011, pp. 2325–2333.
7. C. Ware and P. Mitchell, “Visualizing Graphs in Three Dimensions,” *ACM Trans. Applied Perception*, vol. 5, no. 1, 2008, article 2.
8. C. Ware and G. Franck, “Evaluating Stereo and Motion Cues for Visualizing Information Nets in Three Dimensions,” *ACM Trans. Graphics*, vol. 15, no. 2, 1996, pp. 121–140.
9. D. Bowman and R. McMahan, “Virtual Reality: How Much Immersion Is Enough?,” *Computer*, vol. 40, no. 7, 2007, pp. 36–43.
10. R. Ball, C. North, and D. Bowman, “Move to Improve: Promoting Physical Navigation to Increase User Performance with Large Displays,” *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 07), ACM, 2007, pp. 191–200.
11. K. Reda et al., “Scalable Visual Queries for Data Exploration on Large, High-Resolution 3D Displays,” *Proc. 2012 SC Companion: High Performance Computing, Networking Storage and Analysis*, IEEE CS, 2012, pp. 196–205.
12. A. Knoll et al., “Uncertainty Classification of Molecular Interfaces,” *Int’l J. Uncertainty Quantification*, vol. 3, no. 2, 2013, pp. 157–169.

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