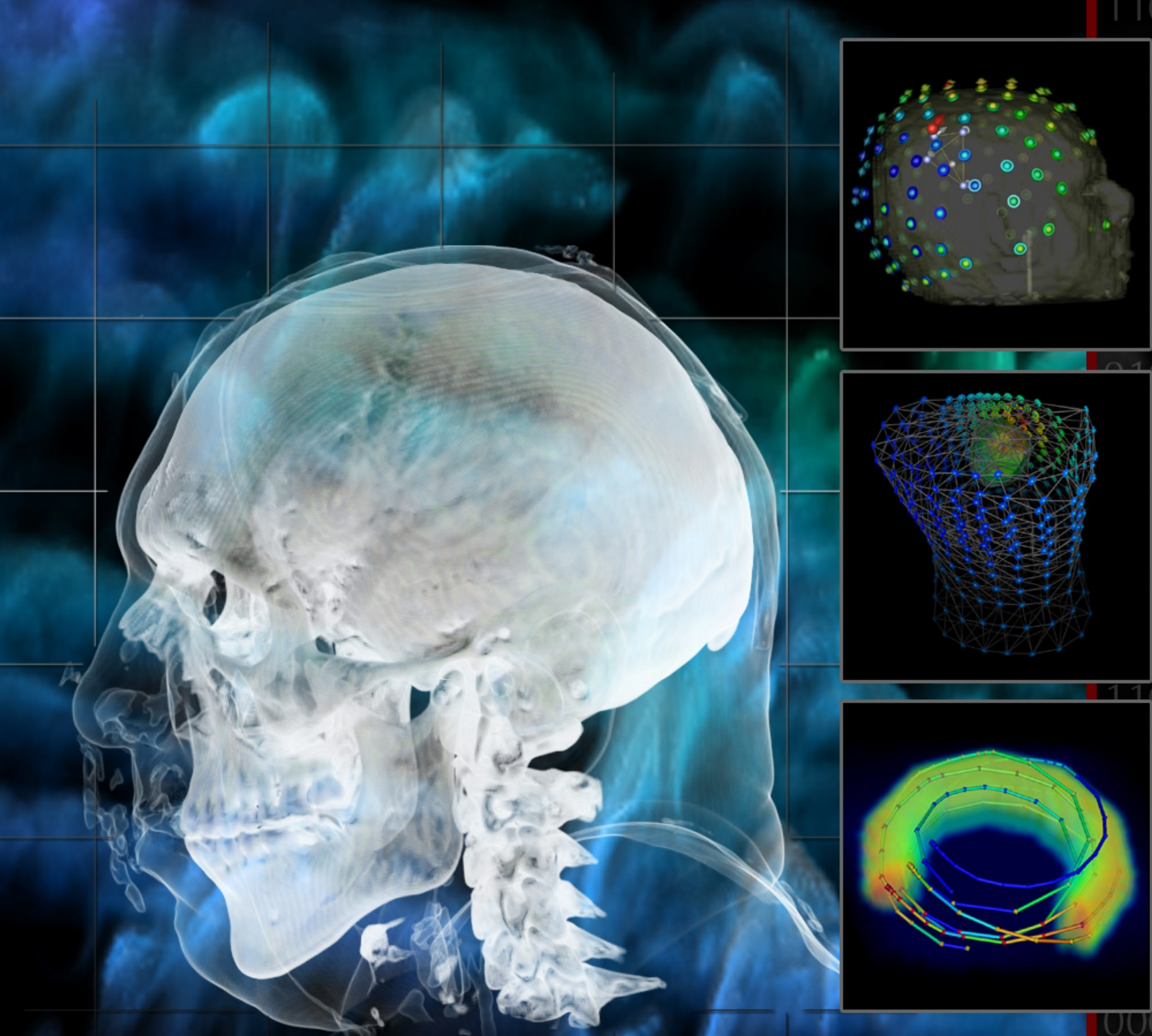
SCIENTIFIC COMPUTING AND IMAGING

INSTITUTE



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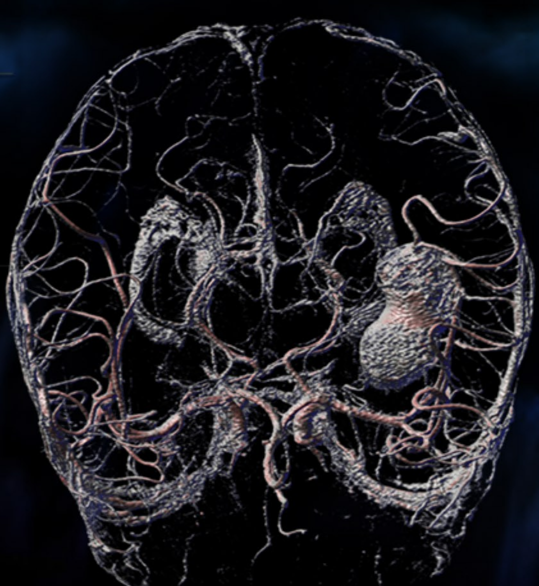
Above: The University of Utah Campus

Cover Insets (top - down):

Inverse EEG source localization,
Forward Simulation from torso tank,
Fusion data visualized in SCIRun

Design and layout by Nathan Galli

Contents:



SCI Institute History

The Scientific Computing and Imaging (SCI) Institute began as a small research group in 1992 when Dr. Chris Johnson joined the School of Computing (then, the Department of Computer Science). The group has grown since 1992, from Dr. Johnson as a single investigator with a few graduate students, to the Scientific Computing and Imaging Institute - a research organization with over 60 faculty, staff, and students.

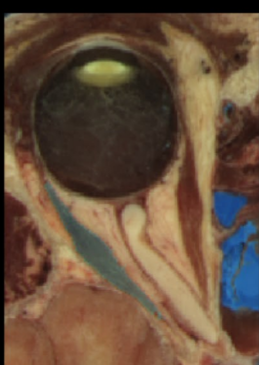
In creating the SCI research group that evolved into the SCI Institute, Dr. Johnson built upon his diverse research background and interests. These include such aspects of scientific computing as inverse and imaging problems, adaptive methods, modeling, numerical analysis, computational problems in medicine, problem solving environments, and scientific visualization.

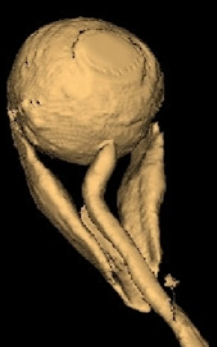
The early focus of SCI research was computational electrocardiography and, more generally, biomedical computing, and these remain major themes of the Institute. From the computational needs created by these applications, new themes arose such as geometric modeling, numerical simulation, and visualization techniques, and eventually, integrated software environments for problem solving. The breadth of the applications has expanded to include bioelectric signals from the brain, medical imaging, surgical planning, reservoir modeling in geoscience, diffusion of air born pollutants in environmental science, and combustion in chemical and fuels engineering.

The Scientific Computing and Imaging Institute has established itself as a leader in scientific computing, scientific visualization, and imaging research. The Scientific Computing and Imaging Institute currently houses two research centers: the NIH Center for Bioelectric Field Modeling, Simulation, and Visualization and the DOE Advanced Visualization Technology Center as well as the NIH BISTI Program of Excellence in Computational Bioimaging and Visualization. We also oversee the SGI-Utah Visual Supercomputing Center. In addition, the Scientific Computing and Imaging Institute is formally associated with other National research efforts: the NSF Partners in Advanced Computational Infrastructure (NCSA PACI) and the DOE Center for the Simulation of Accidental Fires and Explosions. For more information, visit our website at (www.sci.utah.edu).

SCIENTIFIC COMPUTING WITHIN THE SCI INSTITUTE

The overarching goals of the SCI Institute's scientific computing research are to create new techniques, tools, and systems, by which scientists may solve problems affecting various aspects of human life. We believe that to advance the state-of-the-art and create meaningful computational solutions for such complex systems, one needs to advance research in a number of areas within scientific computing, including: visualization, simulation, and modeling. Furthermore, to enable such new algorithmic and software research to have real impact outside of scientific computing and computer science, these components must be integrated with data and application specific knowledge within intuitive software systems, problem solving environments (PSEs) or "computational workbenches."





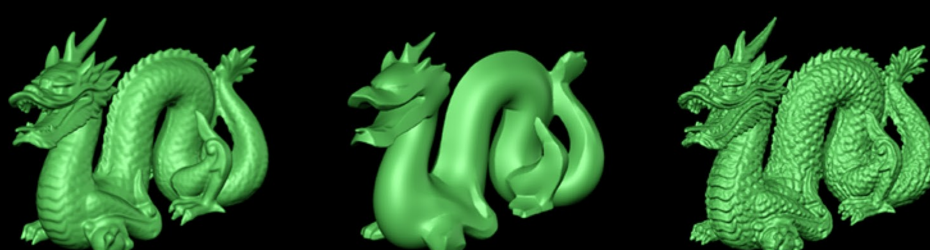
MODELING

The primary focus of our research and development in geometric modeling continues to be the creation of accurate algorithms and software for creating large-scale surface and volume representations of complex, multi-materials geometries. The source data for these models comes from variety of sources, including medical imaging modalities, manual sampling of discrete points via 3D digitizers, and range data.

IMAGE PROCESSING

Image processing and analysis play an important role in many applications of scientific computing and imaging. For example, we are developing a method of correcting Magnetic Resonance Images (MRI) of metabolic brain activity using anatomical MRI images taken during the same imaging session.

Geometric Surface Processing. Processing surfaces via their normal maps allows us to generalize image processing techniques to surfaces. The computational approach uses level set surface models; therefore, we can process complex surfaces of arbitrary topology with ease and the processing does not depend on any underlying parameterization.



Original model | Anisotropic diffusion | High-boost filtering

Segmentation (left). Our research contributions in the area of image segmentation include hierarchical, image-intensity based methods and techniques which model moving interfaces in the image volume. In cooperation with medical professionals, we are exploring the practical application of our segmentation algorithms to real world problems. Shown below is a three dimensional segmentation of the right eyeball, optic nerve, and associated musculature from a section of the Visible Female color cryosection data.

MRI CORRECTION

Intensity inhomogeneity is inherent in MRI data and directly effects the ease with which the images can be segmented or otherwise utilized. This artifact is highly dependent on patient anatomy and the accompanying acquisition protocol. We have developed a method for correcting intensity inhomogeneities using a polynomial estimation of the bias field, which minimizes the composite energy function to find parameters of the polynomial model. The energy function is designed to provide a robust estimation of the bias field by combining measures from histogram analysis and local gradient estimation. Below we show the correction of T2-weighted surface coil brain data by 4th order Legendre polynomials. Figure 1 displays the initial "sum-of-squares" slice of T2-weighted brain data set from 4-surface coils while figure 2 shows the corrected slice.

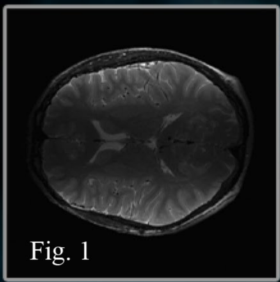


Fig. 1

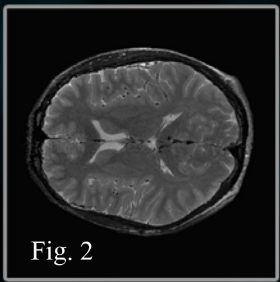
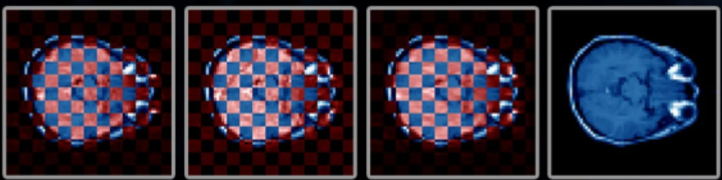


Fig. 2

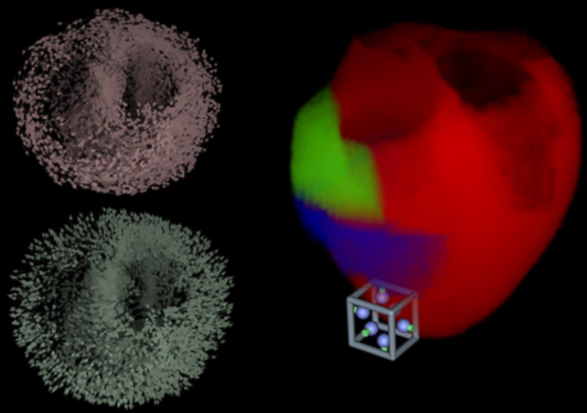
EPI CORRECTION

Image distortions such as global and local distortion are significant drawbacks to the MR imaging technique known as echo planar imaging (EPI). While EPI correction via maps of the magnetic field are the current gold standard, this data is not always readily available. We have developed a method (named "RegMor") of EPI correction that uses image registration and morphing against anatomical MR scans, instead of field maps. Below we display (left to right) the uncorrected, RegMor corrected, and field map corrected EP scans, in red, merged into a checkerboard pattern with the blue non-distorted anatomical scan. In the checkered images, the brain edges from the uncorrected EP scan and anatomical scan are disjointed, while the brain edges of the corrected EP scans and anatomical scans flow evenly into each other.

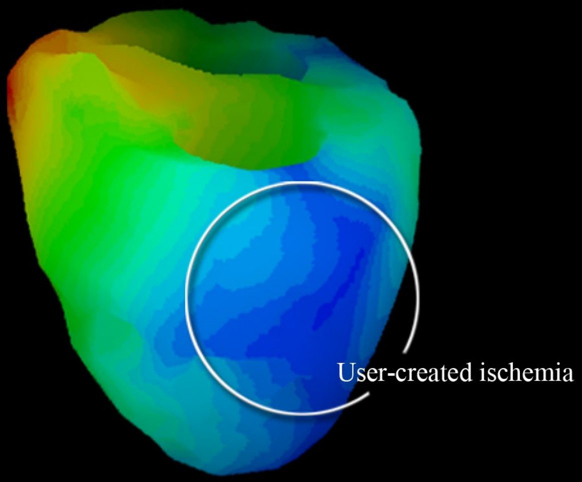


APPLICATION: CARDIOWAVE

We have constructed a set of BioPSE networks for modeling cellular activation in cardiac tissue. These networks use the CardioWave system from Duke University (Craig Henriquez) to simulate cellular activation and propagation through a bidomain finite volume model of a whole heart. The BioPSE system is used for geometrically modeling the domain, and for visualizing the results. Special-purpose tools have been written in BioPSE for converting between BioPSE and CardioWave matrix formats. By bridging the two systems in this way, we can leverage the power of the CardioWave large-scale numerical solvers without having to alter any of the existing CardioWave software.



Above we see the fiber orientations along with the heart model and interactive selection tool used to create ischemia. Below we view the altered heart model visualized in SCIRun.

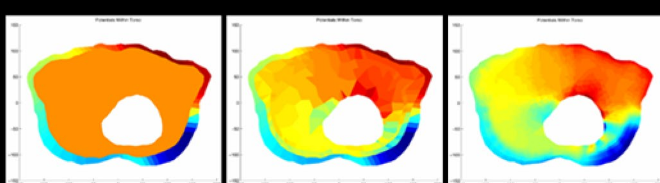


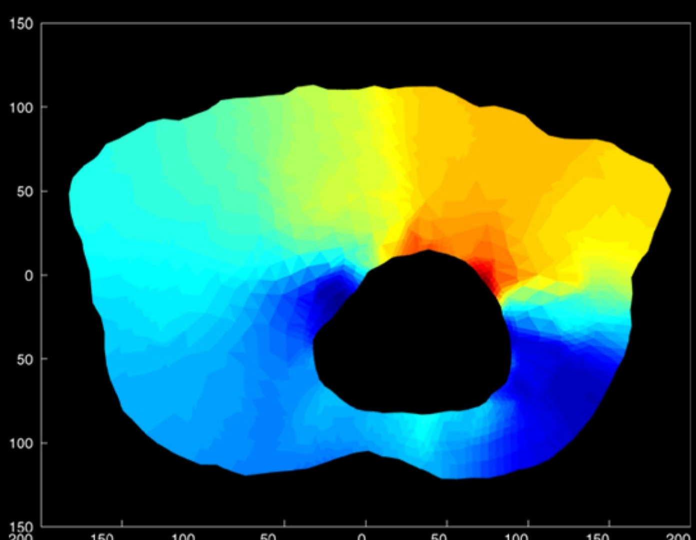
SIMULATION

The SCI Institute research agenda involves developing interactive software tools for large-scale problems in science, engineering, and medicine. This involves designing efficient and accurate modeling, simulation, and visualization techniques and software. The SCI Institute has developed a number of new simulation methods and techniques in the areas of adaptive methods and inverse problems have applied these techniques to problems in science, engineering, and especially medicine, where we have developed physiologically and clinically important scenarios and results. We have done important work in applications of large-scale computing to a class of bioelectric field problems whose solutions have utility in defibrillation studies, including both device design and bioelectric field imaging, important in the detection of arhythmias and in the localization of brain activity.

MULTIGRID METHODS

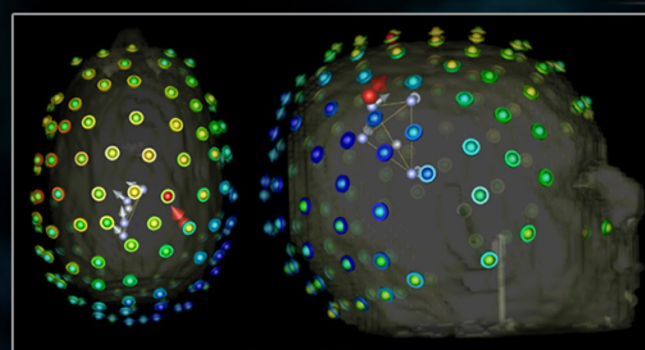
Many approaches to solving the inverse problems involve repeated numerical solutions of related forward problems (for instance, the setup of the lead field matrix). Multigrid methods (shown above) are known as fast and efficient means for solving linear systems arising from the discretization of second-order elliptic PDEs. Optimally designed multigrid solvers exhibit convergence rates that do not depend on mesh size, plus they allow greater control over the regularization. We are currently investigating potential applications of multigrid methods, specifically algebraic multigrid (AMG), to solving inverse problems.





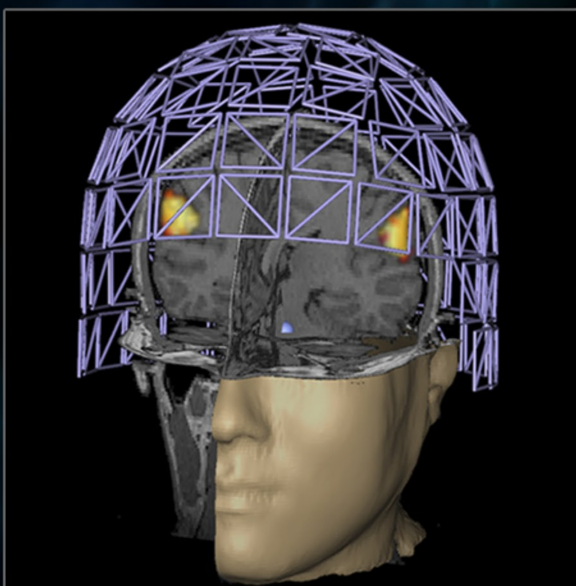
INVERSE PROBLEMS

A common aspect of most imaging modalities is the need to perform reconstruction based on remote measurements from a number of sensors - such reconstructions require the solution to an "inverse problem." The goal of the reconstruction can be structural information, such as the anatomy that comes from classic medical imaging with, for example, magnetic resonance or X-rays. The aim of the inverse solution can also be functional information such as electrical activity or conductivity.

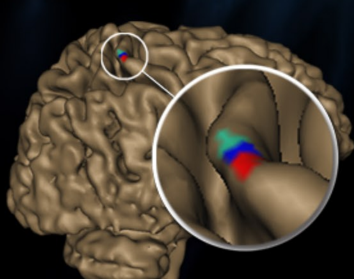


The goal of the inverse EEG (electroencephalography) is to localize a neural source in a realistic model of a patient's head. Given EEG measurements from electrodes placed at known locations on a patient's scalp, and a discretized tetrahedral volume mesh with each node labeled with the appropriate conductivity of the underlying anatomy, we solve a source localization inverse problem to identify the position and moment of an equivalent dipole representing the neural source within the domain that best reproduces the EEG measurements. We approach this application as an optimization problem, iteratively choosing new dipole locations until the algorithm converges on the optimal location.

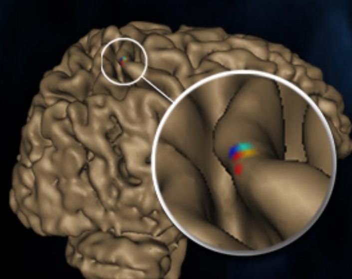
Focusing inversion is an inverse method for reconstructing sharp, focused images from smooth measured data. Applying this technique to the MEG (magnetoencephalography) source localization problem, we are able to resolve multiple focal sources. The composite image shows a patient's head and the sensor locations that correspond to an MEG measurement helmet. Starting with two dipoles placed in the head volume, we have computed simulated MEG values at the sensor sites. Using BioPSE, we can interactively visualize the results. The recovered areas of activation are shown volume rendered in yellow, and are displayed with the original MRI data for reference.



We have implemented a finite element method that uses higher order basis functions to obtain more accurate electric potentials on the brain's cerebral cortex when solving the forward EEG problem. When higher order elements are used, the electric potential on the cerebral cortex is more focused giving a more accurate result than can be determined by using lower order elements.



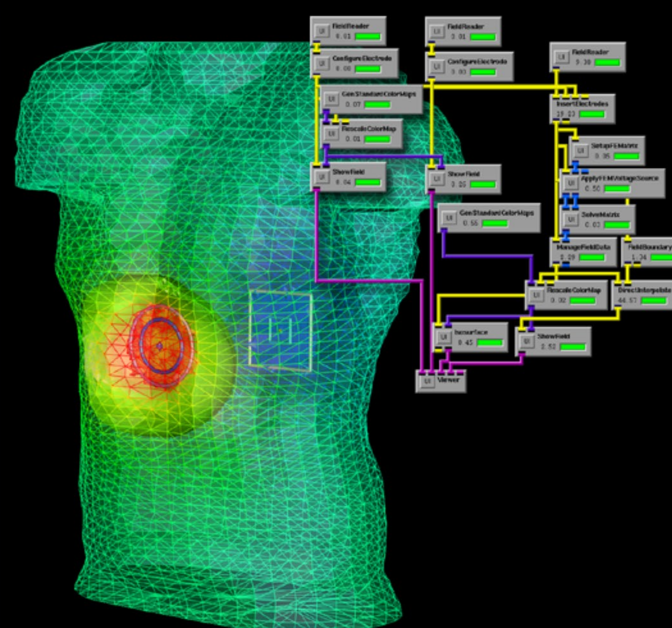
Linear



Quadratic

APPLICATION: DEFIBRILLATION

Bioelectric fields from the heart are responsible for the electrocardiogram (ECG). A goal of computational electrocardiography is to represent the electric sources within the heart. We have developed realistic geometric models of the human thorax, as well as computational tools and software for representing the electric fields in the heart and thorax. Current areas of interest include developing methods to better estimate the electrical activity in the heart from ECG measurements on the body surface, the "inverse problem of electrocardiography." A second specific project in cardiac fields is to develop computation tools for defibrillation. Defibrillators are essential devices in emergency medicine and in recent years have also become implantable by which patients with known instabilities in the electrical activity of the heart can receive potentially life saving protection. The SCI Institute has developed tools for placing electrodes anywhere within an inhomogeneous geometric model of the human thorax and calculating the resulting electric fields.

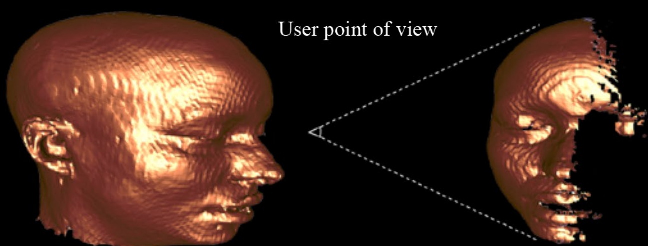


VISUALIZATION

Scientific visualization is the process of creating visual representations to analyze computational or measured data. Typically, the visualization process results in an image, animation, or interactive environment that might include other sensory feedback such as "haptics." Significant portions of SCI Institute research efforts are focused on finding effective ways to visualize large-scale, three-dimensional computational fields.

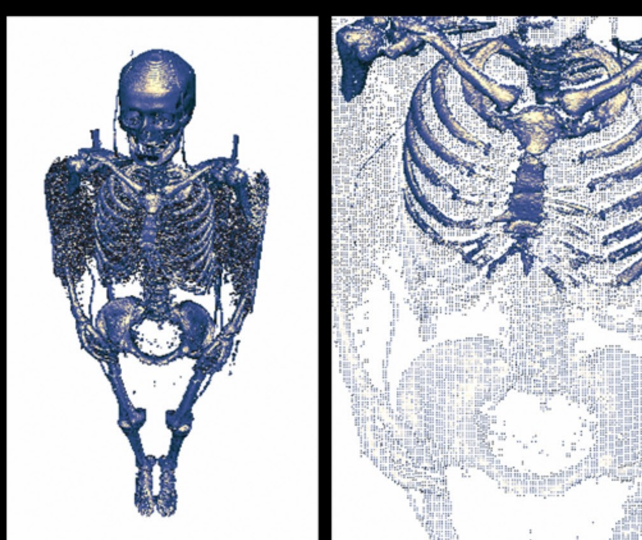
REMOTE VISUALIZATION

View dependent isosurface extraction (shown below) is based on extracting only the visible portion of the isosurface. This approach provides a fast and economical imaging of complex isosurfaces and is especially suited for applications such as remote visualization where many isosurfaces are generated and transmitted over a network.



The user view

The same isosurface from a 90 degree angle to the user view, illustrating the incomplete reconstruction.



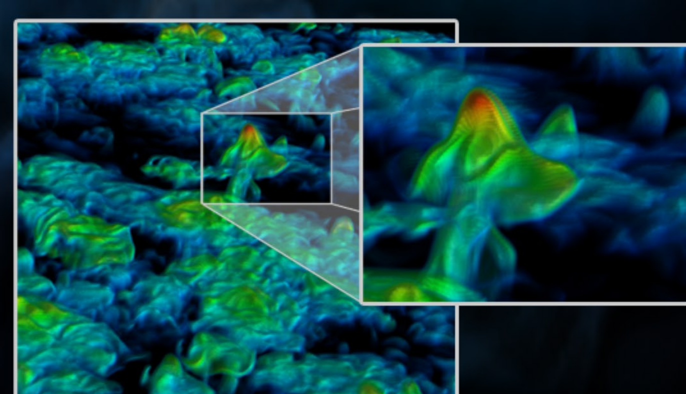
Left: The extracted isosurface as seen from the user view point

Right: A close up. Note that many of the [meta-] cells are represented by points

RTRT

The real-time ray tracer is a rendering system that interactively ray traces an image on a multiprocessor platform. The implementation explicitly traces rays through every screen pixel, paying careful attention to system resources for acceleration. In the following figure, the teapot is a Bezier patch model and the bunny is made up of approximately 70,000 triangles. Also, rays are attenuated through the glass tabletop, giving the green effect along the edge.

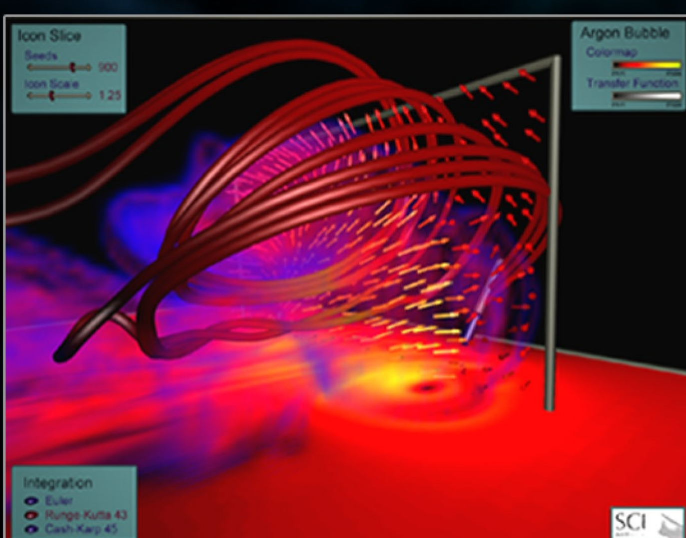
Below we see a volume visualization from shallow cumulus convection. The images were created from a condensed water field 1008x1008x300.



IMMERSIVE ENVIRONMENTS

SCI Institute investigators seek to provide even more complete interaction with data by making use of additional sensory input and control mechanisms in three-dimensional displays. Specific examples include the use of position and motion tracking devices, three-dimensional cursors, and "data gloves" that provide intuitive ways of merging the user and image spatial domains. We also employ "haptic" feedback devices that generate physical forces in the user's hands based on the material properties of the datasets under examination. The goal of this research is a complete immersion of the user into the data providing a more intuitive and efficient interaction than is possible with conventional visualization techniques.

Above are examples of immersive flow visualization. The user interacts with the datasets via the Visual Haptic Workbench (left) and the VSC Wall Display (right). Below is a screenshot of the second application running on a Linux PC

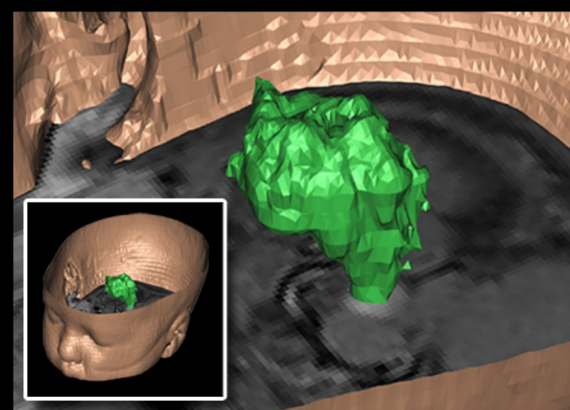


Argon shock bubble dataset provided courtesy of J. Bell and V. Beckner, Center for Computational Sciences and Engineering, Lawrence Berkeley National Laboratory.

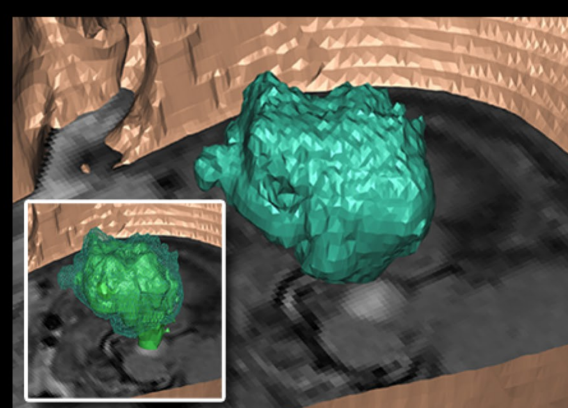
APPLICATION: TUMOR VIS

In 2001 the SCI Institute was approached to use the Institute's advanced visualization techniques to assist with the planning of a tumor operation being performed on a young girl at Primary Children's Hospital. Using SCIRun, we were able to interactively visualize 3-D MRI data for the surgeon on our 8 ft by 10 ft screen. This visualization aided the surgeon in planning the operation. In fact, the surgeon stated that by utilizing the Institute's technology "it was his first night of sleep in 23 years of surgery, that he actually knew where to go and get the tumor out." While the operation was largely successful, remnants of the tumor remain requiring the consideration of further surgical procedures and chemotherapy.

Continued ...

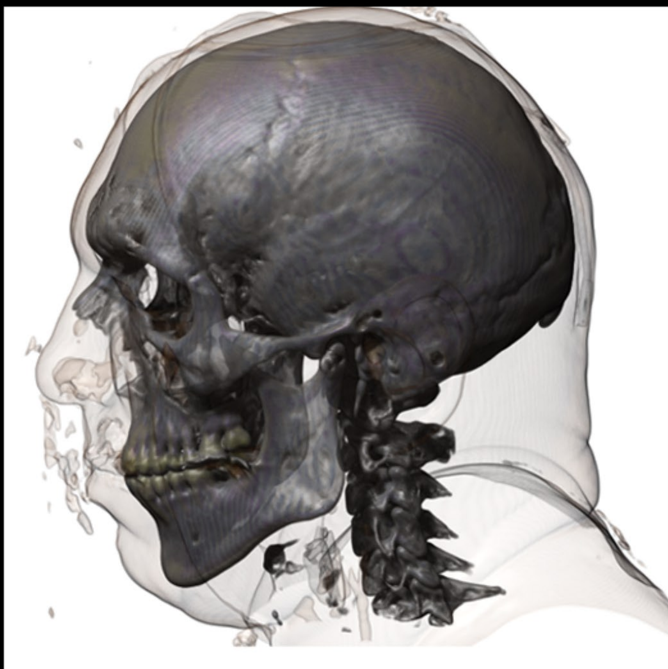


Initial Diagnosis: September 1999



Presurgical Exam: May 2001
Inset: Wire mesh of presurgical exam displayed over initial diagnosis.

VISUALIZATION *Continued*



VOLUME RENDERING

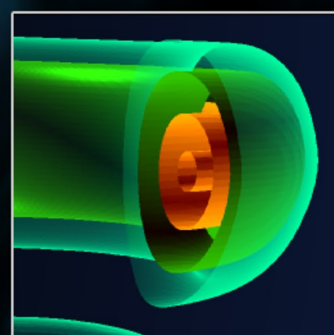
Volume rendering is a technique for visualizing sampled functions of three spatial dimensions by computing 2-D projections of a colored semitransparent volume.

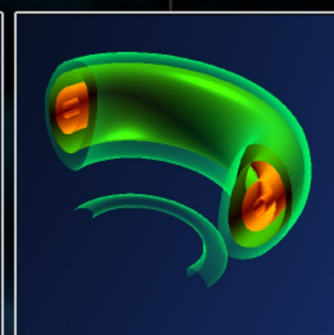
The main advantage of direct volume rendering is that it requires no intermediate calculation of geometric information and thus can be dramatically more efficient than other techniques. SCI Institute researchers have focused on semi-automatic methods for transfer function generation, volume rendering techniques for time-dependent data, and multi resolution volume rendering methods. Research describing a new volume rendering tool for scientific visualization and medical imaging, called Simian, won the Best Paper Award at the IEEE Visualization 2001 Conference.

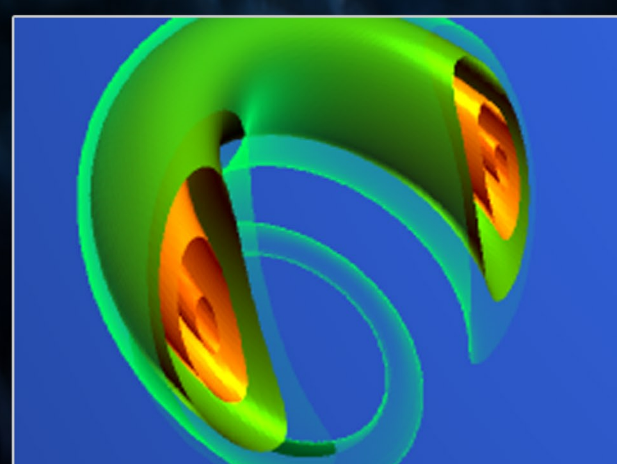
ISOSURFACE EXTRACTION

Isosurface extraction is a powerful tool for investigating volumetric scalar fields. The position of an isosurface, as well as its relation to other neighboring isosurfaces, can provide clues to the underlying structure of the scalar field. SCI Institute research in isosurface extraction techniques has resulted in the "span-space representation" which accelerates the search for isosurfaces in large-scale fields. Additionally, SCI Institute researchers have developed methods for extracting view-dependent isosurfaces and isosurfaces from time-dependent fields.

Below we demonstrate the feasibility of interactively visualizing multiple isosurfaces of 3D tokomak time-dependent data using SCIRun.



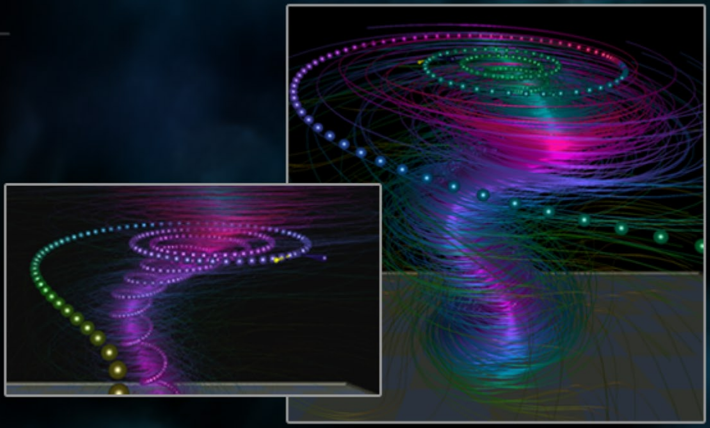




VECTOR FIELD TECHNIQUES

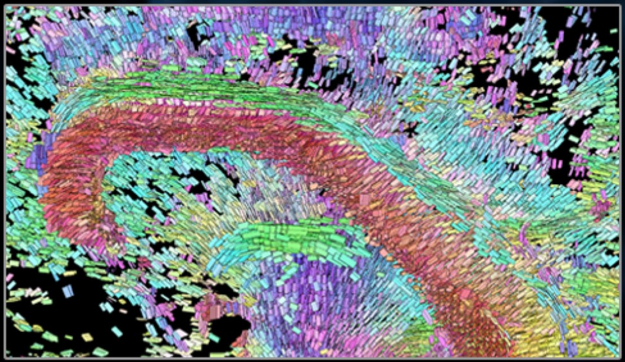
Visualizing vector field data is challenging because no existing natural representation can visually convey large amounts of three-dimensional directional information. SCI Institute researchers have developed local and global visualization techniques to explore three-dimensional vector field data.

Tornado dataset provided courtesy of R. Crawfis, The Ohio State University, and N. Max, Visualization Laboratory, Lawrence Livermore National Laboratory



TENSOR FIELD TECHNIQUES

The simulation of a physical system often requires one to characterize the material properties of the various media within the simulation domain, such as density, electrical or thermal conductivity, or diffusivity. SCI Institute researchers have developed novel methods for visualizing diffusion tensor data generated from MRI scans of the human brain. These visualization methods can be used for analyzing anatomic structures, diagnosing pathologies, and searching for pathways within the brain.



APPLICATION: TUMOR VIS

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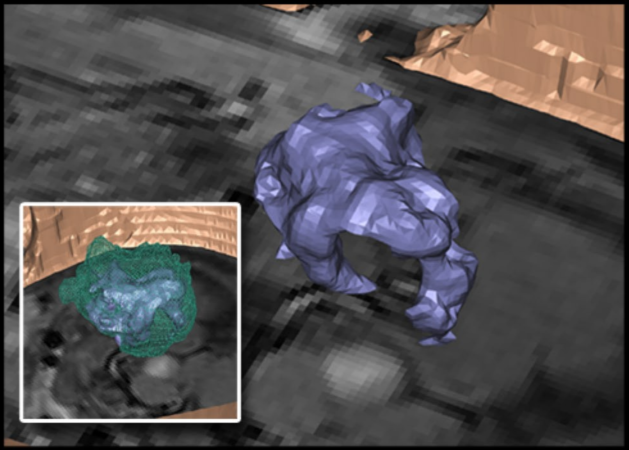


Postsurgical Exam: January 2002
Inset: Wire mesh of presurgical exam displayed over postsurgical results.

Again, the SCI Institute, through its NIH NCRR Center for Bioelectric Field Modeling, Simulation and Visualization had an opportunity to help with this patient's care. In this demonstration, we use BioPSE to comparatively visualize the little girl's brain tumor over time. Several MRI scans are compared in this example including a scan done for the initial diagnosis of the tumor; a scan done 1 year after the tumor diagnosis; a scan done after a surgical resection of the tumor; and finally, a scan done post resection and post chemotherapy treatment. The sets of 2D MRI slices (some with poor resolution) were rendered into 3D volumes and co-registered using a variety of anatomical landmarks. After registration, isosurface algorithms were used to isolate the tumor in each volume. As can be seen in the images, the tumor grows considerably over the year between diagnosis and resection. Additionally, it can be seen that the tumor resection is not complete. The next step in this work will be the examination of the volume after chemotherapy is completed and at time-steps thereafter. It is hoped that using sophisticated co-registering and isosurfacing and rendering algorithms, we can provide a visualization that allows for better size comparisons over time providing for more accurate estimates of tumor growth.

SOFTWARE: PSE/VISUALIZATION

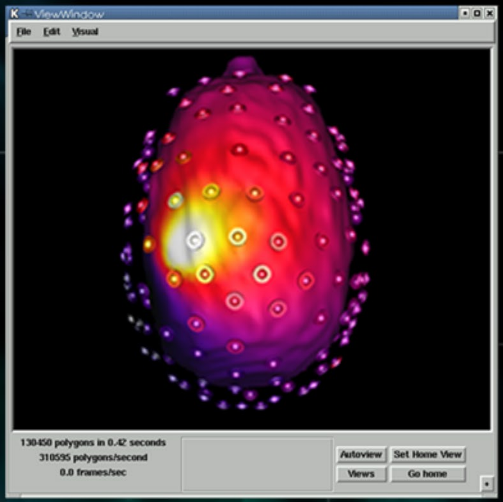
SCIRun/BioPSE/Uintah

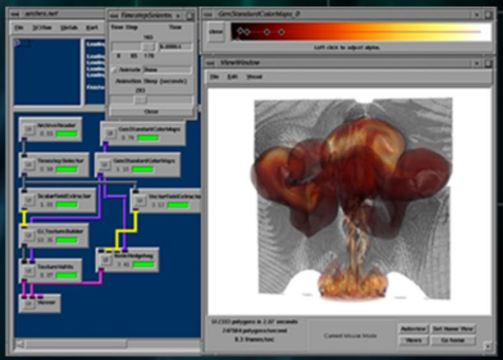
Implementing advanced computational methods and scientific visualization techniques can lead to complicated pieces of software. Coupling these different pieces together in interesting ways further increases the complexity. In order to manage this com-complexity, we perform research in Problem Solving Environments - software that provides scientists with a range of computational tools flexibly integrated into a single environment.

SCIRun is a multifunctional problem solving environment that can be best described as a computational workbench. All aspects of the modeling, simulation, and visualization processes are linked, controlled graphically within the context of a single application program. Creating an integrated problem solving environment for scientific computing involves many significant elements: representation of mathematical and geometrical models; computational solution of the governing equations and visualization of models and results - all within an efficient, parallel software environment. By tackling such a large integrated systems approach, the SCI Institute draws upon its multidisciplinary approach to science and research in geometric modeling, simulation, scientific visualization, and software environments.

SCIRun, which began development in 1992, was the original implementation of the computational framework. Since then, SCIRun and its computational workbench infrastructure have been the origin of many significant application-specific projects. The two major examples are the DOE sponsored Uintah system (currently operated within the CSAFE project), and the NIH-NCRR sponsored BioPSE system. The target applications of the Uintah project are combustion, computational fluid dynamics, and mechanical modeling implemented on large-scale, distributed architectures. The primary goal of the BioPSE project is to create software for geometric modeling, simulation, and visualization for solving bioelectric field problems.

To realize these two significant projects, the SCIRun infrastructure itself has required significant reorganization, extension, and enhancement. Even with these recent changes, SCIRun remains both the core infrastructure of the problem solving environments and the name of the entire ensemble of software. Thus, a user may install and operate the core SCIRun software and also augment its functionality with one or more of the "packages," such as BioPSE. The SCI Institute anticipates that the collection of packages will grow, as the advantages of the SCIRun infrastructure becomes available to scientists and engineers of additional disciplines.





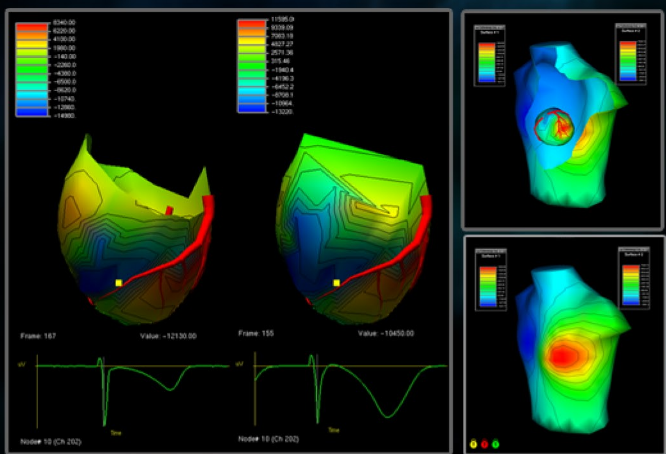
Top: Inverse dipole source localization color-mapped to the surface of the scalp using the BioPSE problem solving environment.

Bottom: 1Gb ASCI 10m heptane fuel fire dataset visualized with vector slice and a multiresolution volume rendering using the Uintah problem solving environment.

SCIRUN/BioPSE is available for download at: http://software.sci.utah.edu

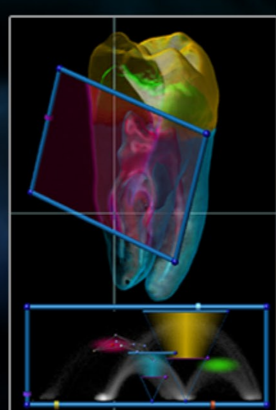
map3d

map3d is an interactive graphics program specifically created to visualize time dependent data sampled over one or more surfaces. Most visualization tools have either a time-based or a space-based perspective on the data; *map3d* supports both in a very flexible manner. The underlying structure of the spatial view is a geometric model of triangles. Mapped to the nodes of this model are time signals, which *map3d* displays on the geometry as color coded renderings. The user can select any number of time signals and view each in its own window.



Simian

The goal of Simian is to make volume rendering more interactive, intuitive, and expressive. Generating images using traditional volume rendering methods can be difficult. Even with a great deal of experience and training, the process of isolating features of interest in a dataset can be one of trial and error. Simian's combination of hardware based volume rendering (for interactivity), direct manipulation widgets (for intuitiveness), and multi-dimensional transfer functions (for expressiveness) minimizes the trail and error often associated with volume rendering and allows scientists, engineers, and physicians to efficiently answer important questions about their data.



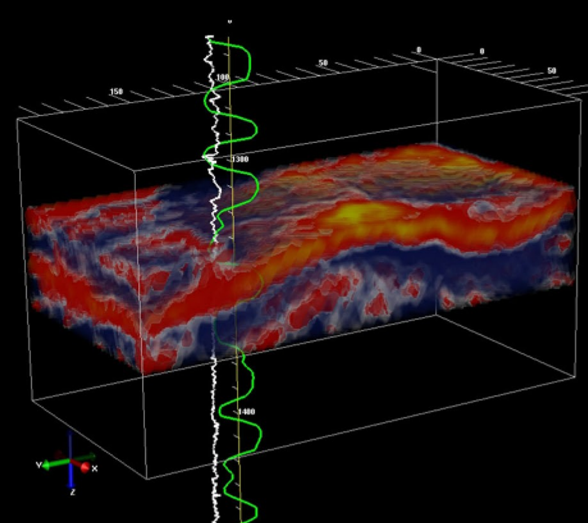
CT Scan of a tooth rendered in Simian with the interactive transfer function widgit.

APPLICATION: IN THE FIELD

The SCI Institute continually seeks active collaborative research projects with applications to real world problems. Here we show a large-scale geoscience simulation and visualization. Together with members of the Energy Geosciences Institute (EGI) at the University of Utah, and a major U.S. oil company, SCI researchers have incorporated a three-dimensional oil and gas reservoir simulator into the SCIRun problem solving environment.

Using SCIRun the researcher can configure a simulation, monitor and control it during the execution, and then initiate a new simulation based on the final or partial results. Real time feedback during the simulation is in the form of a graph of the convergence of the solution and presentation of intermediate solutions. The user can change the target error for the simulation in real time, examine the visualization of the intermediate results, or manipulate the input to the simulation.

One special feature of the simulator is the ability to move well locations interactively during the simulation and thus explore many "what-if?" scenarios. The user can also change the strength of the flow of a well and determine whether the well is a "producer" or an "injector." These changes can be applied while the simulation is in progress, which in turn will cause the simulation to stop and restart automatically based on the new parameters.



REMOTE COLLABORATION

ACCESS GRID

Since the late 1980's, the National Center for Supercomputing Applications (NCSA) has been developing collaborative technologies to fulfill the needs of today's researchers. Starting with the Mosaic project, the NCSA now drives the development of the Grid Alliance. This Alliance harnesses the tools and expertise of almost 50 universities and institutions throughout the country. This collective infrastructure is now referred to as the Grid.

The Grid is a real-world attempt to connect resources and combine computing power over the Internet. This infrastructure includes ubiquitous computing, wireless networking, groupware, distributed supercomputing, unique authentication, and a host of other novel and cutting-edge technologies.

To accompany the Grid technology, the Access Grid was developed to connect the most important resource, people. The purpose of the technology is to provide a standardized platform of primarily open source software and "off-the-shelf" components. What this means is that a research group can go to their favorite hardware vendors and build the baseline Access Grid tools (commonly known as an "Access Grid Node").

The SCI Institute has added a few extra features to its node that allows for a fully OpenGL accelerated tiled desktop capable of running a resolution of 3000 by 800. Our upgraded AG facility is capable of driving a display in stereo and providing digital video outputs for future projector technology. A 5.1 Dolby Digital sound system rounds out the enhancements to the Institute AG node.

The SCI Institute not only collaborates with researchers around the world on the Access Grid, we also collaborate across campus. The Center for High Performance Computing and the Center for Advanced Medical Technologies both have active Access Grid Nodes.

Simulation of remote vis using the Access Grid

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