Vector Field VISUAL Data Analysis for PETASCALE

State-of-the-art computational science simulations generate large-scale vector field datasets. Visualization and analysis are key aspects of obtaining insight into these datasets and represent an important challenge. This article discusses possibilities and challenges of modern vector field visualization and focuses on methods and techniques developed in the SciDAC Visualization and Analytics Center for Enabling Technologies (VACET) and deployed in the open-source VisIt tool.

Introduction

Visualization — the transformation of abstract data (whether observed, simulated, or both) into readily comprehensible images (figures 1 and 2) — has proven to be an indispensable part of the scientific discovery process. A number of new techniques and tools have been developed to make visualization more accessible to the scientific community.

Vector fields are one of the more complex areas of scientific visualization. For example, the analysis of fluid flows that govern natural phenomena on all scales from the smallest (such as Rayleigh–Taylor mixing of fluids) to the largest (supernovae explosions, sidebar "Supernova Magnetic Field Visualization" p13) relies crucially on visualization to elucidate the patterns exhibited by flows and the dynamical aspects driving them (figures 3 and 4, p12). Processes typically described by vector fields — such as transport, circulation, and mixing — are prevalently non-local in nature. Because of this specific property, methods and techniques developed and proven successful for scalar data visualization are not readily generalized to the study of vector fields. Therefore, while it is technically feasible to apply such methods to directly derived scalar quantities such as vector magnitude, the resulting visualizations often fall short of providing an explanation of the mechanisms underlying the scientific problem.

Broadly, vector field visualization techniques fall into three categories. Glyph-based methods depict the behavior of a field by mapping vectors to a geometric representation (such as arrows); they convey only a very local perspective. Feature-based techniques typically aim at identifying regions of interest by comparing a vector field locally to an empirical definition of a pattern of interest, for example vortices and shocks. Both classes are limited in their use as general visualization tools since they fail to capture essential aspects of vector fields or work in a very narrow, problem-specific context. The third class of techniques, integration-based methods, focuses on deriving visualization from the study of integral curves of a vector field. Intuitively interpreted as the trajectories of massless particles transported by a vector field, such curves capture the evolution of material quantities over variable time-scales and are thus a broadly applicable tool to study, visualize, and illustrate vector fields and their non-local and dynamic aspects.

The focus of this article is to describe recent research efforts in the field of integration-based vector field visualization within the DOE SciDAC Visualization and Analytics Center for Enabling Technologies (VACET). Working on both theoretical and practical aspects of integra-

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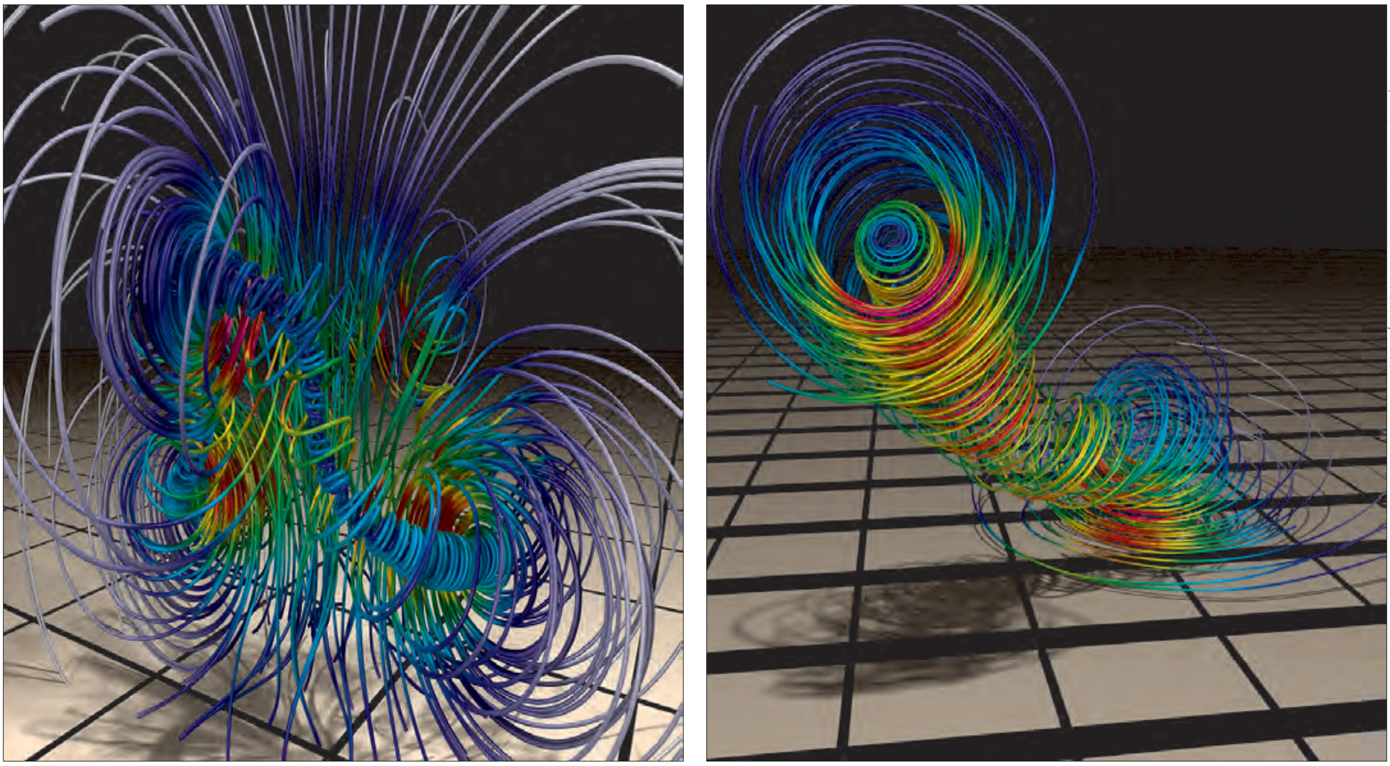

Data: D. Martin, LBNL Applied Numerical Algorithms Group/APDEC

Figure 1. *Streamlines in different time steps of a vortex merger dataset.*

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Figure 2. *A stream surface illustrates turbulent flow into a tank.*

tion-based visualization, VACET researchers have developed a number of new visualization techniques, and tools to make these techniques accessible to the scientific community. After providing a brief look at some of the fundamentals of integration-based visualization, we describe both the basic research centered on novel visualization methods and the current state of, and future plans for, integration into VisIt, the open-source visualization tool VACET uses to deploy research results.

Integral Curves and Visualization

Integral curves are one of the oldest and most prevalent vector field visualization techniques. They were originally developed to reproduce physical flow visualization experiments based on small, neutrally buoyant particles.

Technically, an integral curve is a curve with a tangent that is parallel to the vector field at every curve point. Among all such admissible curves, individual curves are determined by selecting an initial condition, or seed point, that the curve originates from

P. Fischer and A. Obabko, ANL

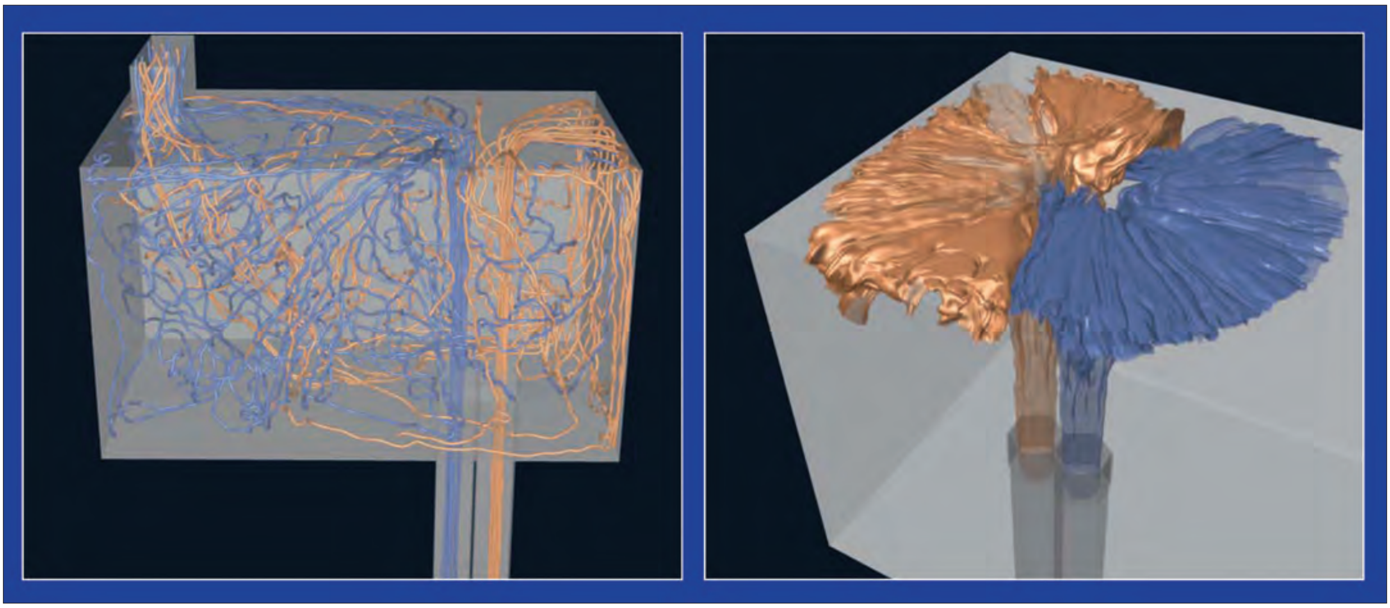


Figure 3. *Thermal convection analysis. Streamlines and stream surfaces of a thermal convection dataset illustrate the mixing of air in a box. Warm (orange) and cold (blue) air enter the box through two inlets. Although the warm air dominates one side of the box, both temperatures mix before ultimately exiting through the outlet in the upper right. From this streamline visualization (left), it becomes apparent that while hot and cold air do indeed mix, the mixing is not entirely optimal since no hot air penetrates into the lower left corner of the box. A stream surface visualization (right) shows that the streams stay separated for some time after entering the box. The time-varying simulation was conducted by Paul Fischer and Alex Obabko (ANL) as part of an INCITE run using the Nek5000 spectral-element code. It consists of 23 million unstructured elements over 3,600 time steps (only one time step was used for these images).*

Data: M. Rütten, DLR Germany

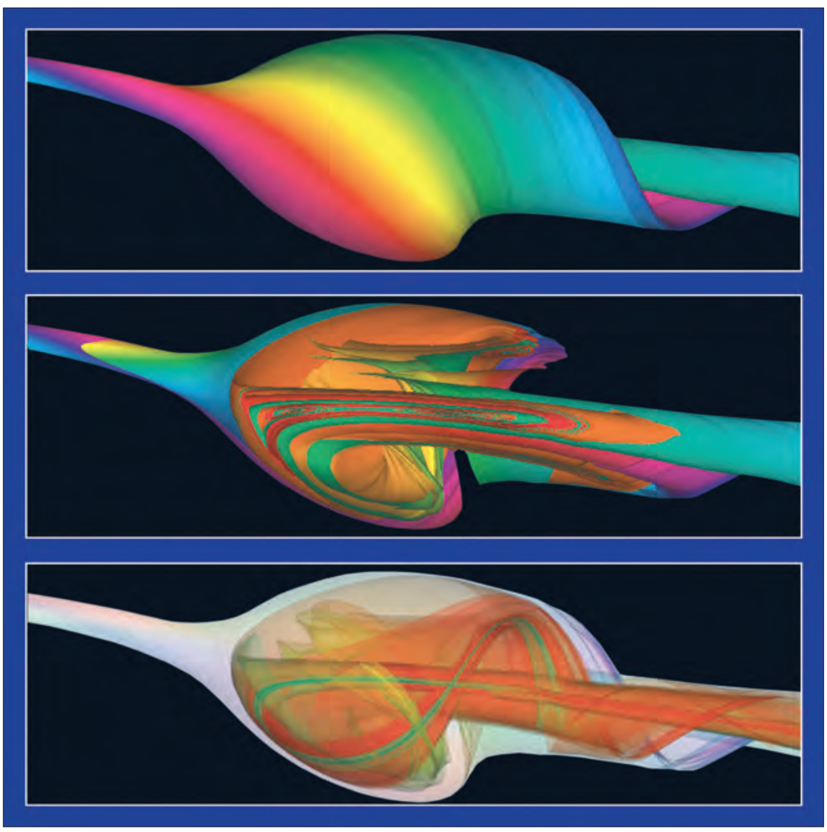


Figure 4. *These images show a stream surface flowing through a vortex breakdown bubble. After entering the bubble, the flow re-circulates, stretches, and folds many times before leaving the bubble at the rear end. While the opaque surface (top) only conveys the basic shape, applying a clipping plane (middle) or transparency (bottom) reveals the complex inner structure of the bubble.*

or passes through. The mathematical interpretation of integral curves as the solutions of ordinary differential equations coincides with that of massless point particles that are advected along the vector field. This intuitive interpretation shows that integral curves are ideal tools to study non-local phenomena like transport (where do particles go?), mixing (how strongly do particles mingle?), and circulation (are trajectories closed?). Moreover, this type of analysis can be performed qualitatively, by directly visualizing integral curves as particle trajectories, or quantitatively, by computing many trajectories and performing, for example, statistical analysis.

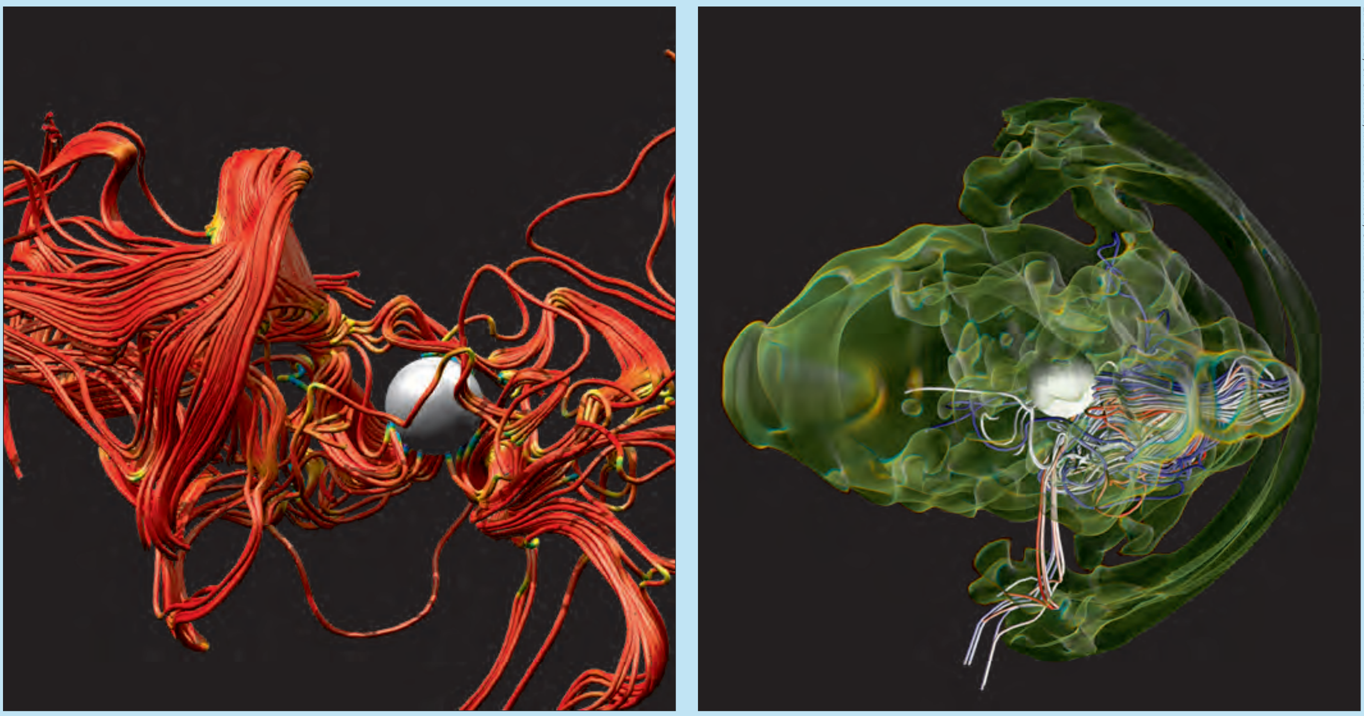
Integral curves are applicable in many different settings because the only theoretical requirement on existence and uniqueness is the continuity and boundedness of the vector field they are defined over. This condition can be fulfilled for virtually all kinds of discrete vector fields from simulation or measurement using interpolation. Hence, integral curves are broadly useful as vector field visualization primitives and apply to both stationary and time-varying vector fields.

The ability to study transport through integral curves also offers an interesting change of perspective. Instead of considering the so-called Eulerian perspective — that is, the value and evolution of vector field-transported scalar quantities at fixed locations in space — the Lagrangian view examines the evolution from the point of view of an observer attached to a particle moving with the vector field.

Supernova Magnetic Field Visualization

The search for the explosion mechanism of core-collapse supernovae and the computation of the nucleosynthesis in these spectacular stellar explosions is one of the most important and challenging problems in computational nuclear astrophysics. Core-collapse supernovae are the most energetic explosions in the Universe, releasing 10^{53} erg of energy in the form of neutrinos of all flavors at a staggering rate of 10^{57} neutrinos per second and 10^{45} Watts, disrupting, almost entirely, stars more massive than ten solar masses and producing and disseminating many of the elements in the Periodic Table, without which life would not exist. They are a nexus for nuclear physics, particle physics, fluid dynamics, radiation transport, and general relativity, and serve as cosmic laboratories for matter at extremes of density, temperature, and neutronization — conditions that cannot be produced in terrestrial laboratories — and for physics beyond the Standard Model.

The collapse of the massive star's core results in the formation of an outgoing shock wave that eventually disrupts the entire star, resulting in a supernova. Along the way, the shock temporarily stalls and experiences the stationary accretion shock instability (SASI), which causes large deviations from spherical symmetry. This appears to be important to the supernova explosion mechanism and may be responsible for spinning up the collapsed core, a nascent neutron star, into a pulsar. Open research questions include the extent to which the SASI may generate magnetic fields and the role of magnetic fields in the creation of supernovae (figure 5).



E. Endeve, C. Cardall, and R. Budiardja, ORNL and U. Tennessee–Knoxville

Figure 5. *These images illustrate the nature of the magnetic field around the core using streamlines. The simulation was performed using GenASIS, a multi-physics code used for the simulation of astrophysical systems involving dense matter. It was run on Jaguar at NCCS by Eirik Endeve, Christian Cardall, and Reuben Budiardja (ORNL and University of Tennessee–Knoxville). The visualization was generated using the parallel streamline functionality in VisIt on 512 processors.*

While both approaches are technically on equal footing, the Lagrangian perspective allows a more natural and intuitive description and analysis of the overall behavior. Consider for example the case of combustion: fuel burns while it is advected by surrounding flow; hence, the burning process and its governing equations are primarily Lagrangian in nature. A secondary but nevertheless important benefit of the Lagrangian perspective is an increased independence from a specific frame of reference.

Computationally, integral curves are approximated using numerical integration schemes. These schemes construct a curve in successive pieces: starting from the seed point, the vector field is queried in the vicinity of the current point and an additional curve piece is determined and appended to the existing curve. This sequence is repeated until the curve has reached its desired length or leaves the vector field domain. While it is trivial to parallelize the calculation of multiple integral curves on a small dataset (by replicating the data and parallelizing over the integral curves), it is very difficult to parallelize the calculation of one or more integral curves on a large dataset. The non-local, non-linear nature of

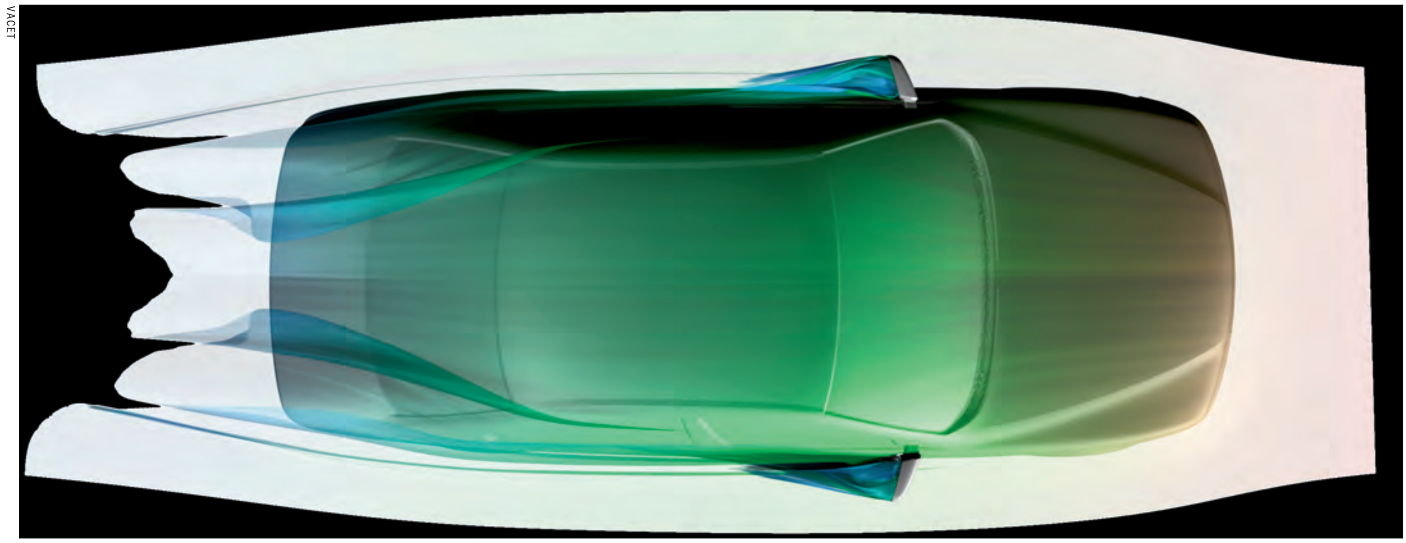


Figure 6. *An integral surface illustrates the flow around a car.*

particle advection implies that particles can traverse almost arbitrary parts of a dataset that must be brought into memory. VACET researchers have evaluated existing techniques and have developed new parallelization strategies that allow for scalability of integral curve computation, allowing the application even on very large datasets.

A number of visualization algorithms that are built on integral curves have been developed over the past decades. The simplest method, the direct depiction of trajectories as streamlines (in the stationary case) and pathlines (in the time-varying case) is often able to quickly yield a visual impression of the basic vector field structure. In a dynamically changing vector field, pathlines reflect the time-dependent nature of the field better than streamlines. However, the increased amount of data processing required to compute pathlines can be a reason to limit the visualization to streamlines. While these direct depictions are often sufficient for a first inspection, there are some inherent limitations. If too many integral curves are depicted simultaneously, the resulting image is visually ambiguous because the individual lines are not well separated. VACET researchers have addressed these visual problems by developing methods to compute integral surfaces, as described below. For some problems, integral curves take on the role of an elementary building block to deliver more abstract visualizations, such as with topological methods (sidebar "Visualizing Magnetically Confined Fusion" p18).

Overall, integral curves are fundamental building blocks of vector field visualization. As described below, the VisIt visualization system offers a robust implementation of integral curves over a variety of mesh types and data formats and offers ready-to-use, scalable vector field visualization capabilities in this context.

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Integral Surfaces

Integral surfaces (figure 6) represent a natural generalization of integral curves. Instead of depicting an integral curve emanating from a single seed point, integral surfaces capture the simultaneous evolution of a continuum of particles that emanate from one- or two-dimensional seed sets, such as lines or surfaces. Depending on the type of seed set, and the chosen visualization, these surfaces have different names (figure 7).

Path surfaces represent a set of integral curves that are seeded on a one-dimensional curve at a single point in time. Intuitively, this corresponds to the simultaneous release and evolution of infinitely many particles forming the seed curve. The surface traversed by these particles then forms the path surface. Hence, path surfaces represent the advection of the seed curve through the field.

A slightly different approach underlies streak surfaces. Particles are seeded from a curve, but in contrast to path surfaces, they are seeded continually over a specified time interval. The intuitive interpretation is that of dye released into a flow at the locations of the seed curve. The dye forms a surface sheet — a streak surface. For such surfaces, it is not feasible to depict the entire volume traversed by the particles in a single frame. However, streak surfaces lend themselves well to animated visualizations that illustrate the general time-dependent behavior of a flow.

Integral surfaces are preferable over integral curves in many situations. For the case of presentation visualization — that is, visualization with the intent of conveying specific aspects of a dataset — they provide an ideal tool because they have strong illustrative character. Furthermore, the visual quality of images generated from such surfaces is often vastly superior to those obtained using a large number of integral curves. If used in large numbers, the latter

DATA: M. RÜTTEN, DLR GERMANY

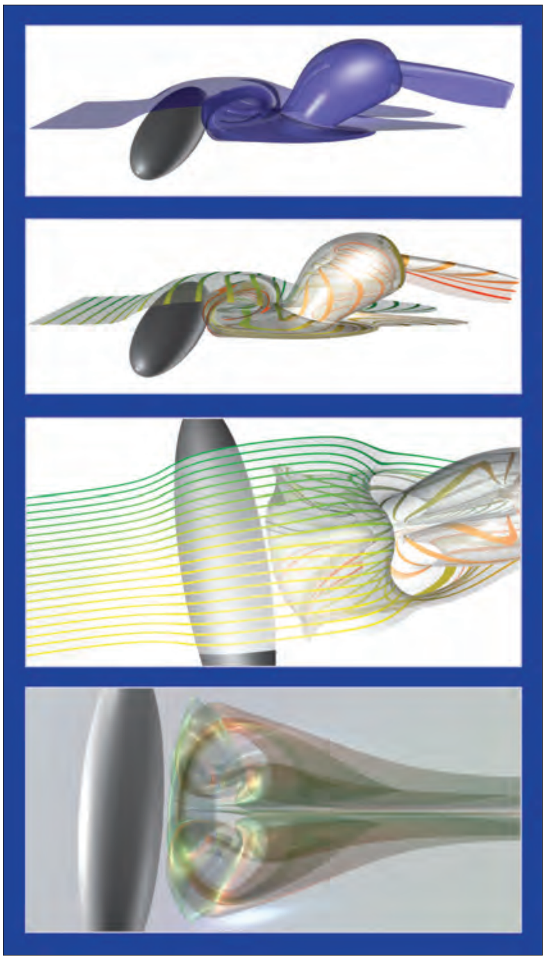

Figure 7. *Various integral surfaces depicting the formation of a vortex system behind an ellipsoid that is surrounded by the flow of water. Textures (middle images) highlight different dynamic aspects of the flow by highlighting particles, time lines, and streak lines.*

DATA: C. GARTH, UC–DAVIS

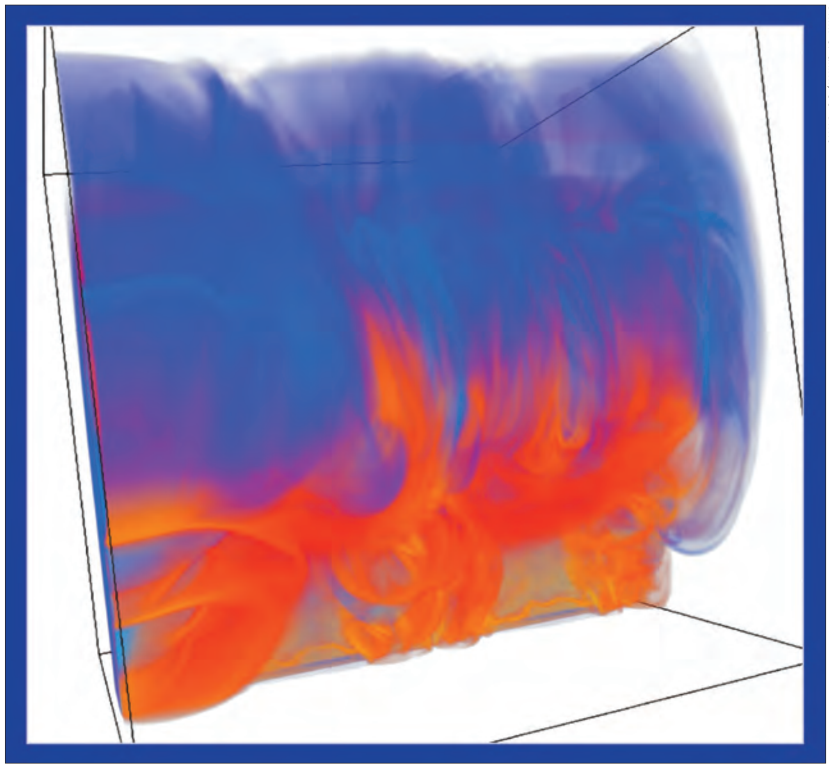

Figure 8. *Translucent volume rendering of the time-varying FTLE fields (red is forward time, blue is backward time).*

tend to result in cluttered visualizations that do not convey the three-dimensional nature of vector field structures. Typical phenomena, such as folding, curling, and divergence of integral curves, aggravate these problems. Integral surfaces, on the other hand, can provide spatial cues by means of physically correct shading. The natural visual coherence of the seed set points is inherited by the surfaces. Within VACET, researchers have developed and evaluated a variety of approaches to further augment the visualization quality of integral surfaces through the application of high-quality transparent rendering and surface textures that encode such information as seed point location and seeding time into the surface color. Through this, expressive visualizations of even very complex flows are easily obtained.

While powerful as visualization primitives, integral surfaces are hard to approximate correctly. This difficulty is a consequence of the often strongly non-linear nature of advection because it induces divergence, shearing, twisting, and folding in the surfaces. Typically, an integral surface is discretized by a finite set of integral curves that form a skeleton of the surface; failing to adapt the skeleton results in a surface that contains extreme rendering artifacts. VACET researchers have built on existing approaches to enable the computation of integral surfaces over very large vector fields. This is achieved by propagating the integral curve skeleton in a way that keeps vector field evaluations closely localized in space and time. This enables a distributed treatment of large vector fields. The corresponding algorithms are planned for inclusion into the VisIt visualization tool in the near future.

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Lagrangian Visualization and Analysis

The visualization techniques discussed above are centered on direct representation of the evolution of a set of particles as they are advected throughout a vector field. A different class of visualization techniques, also built on integral curves as the elementary primitive, focuses on Lagrangian analysis and visualization by deriving information from the movement of all particles under advection in a vector field. In this context, the recently introduced notion of a so-called finite-time Lyapunov exponent (FTLE) has demonstrated great potential toward insightful visualization of the dynamic structure of vector fields. The basic idea consists of transporting particles over a short time interval and measuring an average exponen-

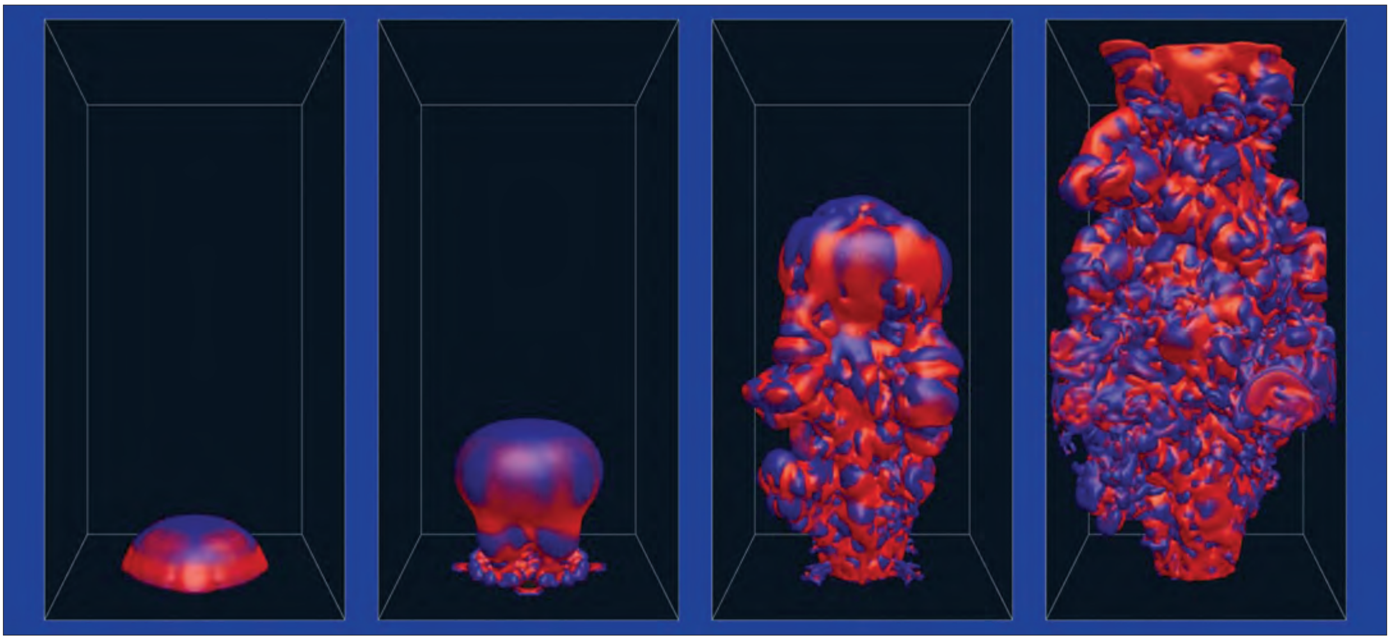


Figure 9. *Direct volume rendering of the time-varying FTLE fields (red indicates the forward-time exponent, blue shows the backward-time exponent) for four time steps, illustrating the formation of turbulence in a high-speed jet entering a domain of stationary fluid. Individual turbulent structures and structure size and distribution can be observed directly from the volume rendering.*

The potential for insight from this type of visualization is a crucial aspect of vector field visualization.

tial separation rate between closely neighboring particles over a finite time.

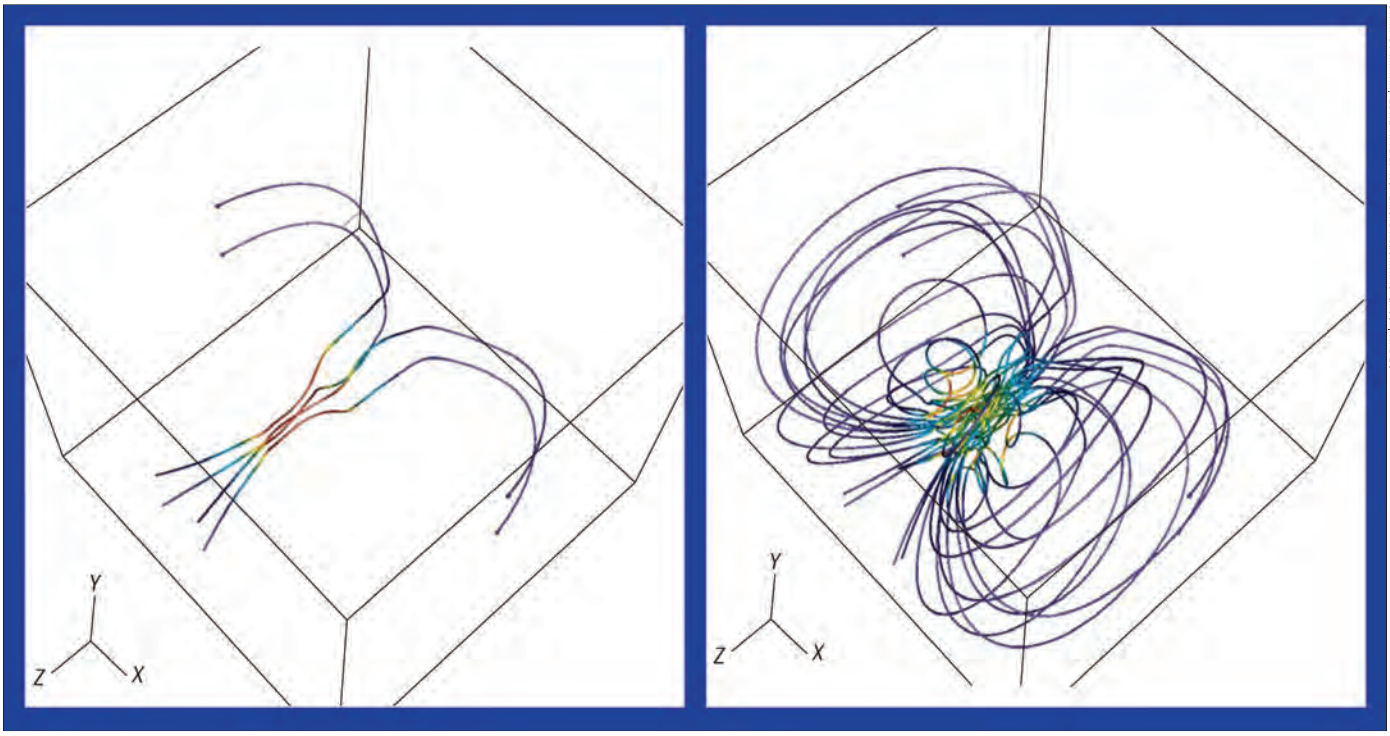
For particles transported forward in time, a locally large exponent at a given point indicates strong divergence or separation of the particles contained in the neighborhood of this point. Conversely, transporting particles backward in time (which amounts to identifying where the particles in the point neighborhood originated from in the past) yields a large exponent in those locations that exhibit strong particle convergence. The two scalar fields of exponents for forward- and backward-time advection can be directly visualized using traditional scalar visualization techniques, such as volume rendering.

The key property that provides meaning to FTLE fields beyond a simple visual encoding of particle divergence and convergence is the fact that these fields indicate Lagrangian coherent structures (LCS) in the form of ridges (lines and surfaces) along which the exponents take on locally maximal values. It can be shown that LCSs are strongly connected to the mathematical interpretation of vector fields as dynamical systems by taking on the role of separatrices of the vector field. The identification and visualization of such separatrices admits direct insight into the global, time-varying dynamics of the flow by visually separating regions of differing particle behavior (figure 8, p15).

For example, particles circulating in a vortex close to its boundary take a different path than those particles that are flowing past the vortex. Consequently, they exhibit strong divergence, which is reflected in a large finite-time exponent. Thus, the FTLE field encodes the vortex boundary — where particles separate — directly (figure 9). Thus, direct depiction of these fields often yields an excellent overview of the vector field behavior. Beyond straightforward visualization through direct volume rendering, FTLE fields can also serve to study a vector field indirectly through the application of readily available visualization methods developed for scalar fields.

The definition and computation of FTLE fields are deceptively simple. In general, all that is required is the advection of a sufficiently dense set of particles that span the domain of interest and the successive measurement of the separation exponent. Sufficient density, however, often requires millions or even billions of particles advected through the vector field, and then a corresponding number of integral curves must be computed. Thus, Lagrangian visualization borders on the infeasible even for vector fields of medium size and complexity. Yet, the potential for insight from this type of visualization is a crucial aspect of vector field visualization.

To remedy this situation, VACET researchers have developed novel algorithms that allow incremental adaptive approximation of FTLE fields over a domain of interest. By adapting the resolution of the computation to the complexity of the FTLE fields themselves, the number of required integral curves is significantly reduced. Additionally, utilizing distributed computation brings the computational effort of FTLE visualization to a feasible level and allows scaling to very large time-dependent datasets.



Data: D. Martin, LBNL Applied Numerical Algorithms Group/APDEC

Figure 10. *An illustration of the qualitative difference between integral curve results using a naive integration approach (left) and dual-mesh interpolation with explicit block boundary treatment (right). The streamlines (left) accumulate enough error that they wrongly exit the domain early. The dual-mesh interpolation with explicit block boundary treatment (right) is the more accurate reproduction of the vortex structure present in the dataset.*

AMR Vector Fields

Adaptive mesh refinement (AMR) is a highly effective discretization method for a variety of physical simulation problems and has recently been applied to the study of vector fields in flow and magnetohydrodynamic applications. AMR represents the domain as a set of nested rectilinear grids at increasing resolutions. Grids are ordered in levels of resolution, and finer levels replace information at locations of the domain they overlap. Thus, AMR combines the adaptivity of unstructured meshes with the implicit connectivity of regular grids, and adds only a little overhead in the form of a box layout description.

Vector field visualization using integral curves faces two challenges in this setting. First, AMR vector fields are typically represented in cell-centered fashion with one vector per cell; thus, an interpolation scheme must be chosen to make the vector field continuous. The commonly used approach of averaging cell information onto the mesh nodes and then interpolating tri-linearly, however, results in a strong smoothing effect on the data. Second, resolution level boundaries, if treated naively and combined with cell-averaged interpolation, induce discontinuities of interpolation that can lead to significant errors during integral curve propagation and reduce the overall correctness and accuracy of the visualization.

VACET researchers have examined these problems and performed a comparative analysis of several interpolation schemes on AMR meshes (figure 10). It was determined that the so-called dual-mesh interpolant, which interpolates the cell-centered values directly without averaging yields, results in improved accuracy. While conceptually simple, this interpolant requires additional information on the boundaries of resolution blocks (ghost cells) that, if not present in existing data, must be derived from coarser levels. Furthermore, the explicit treatment of resolution level boundaries during the integration process can further improve the accuracy and correctness of the generated integral curves, resulting in a robust and accurate integral curve algorithm over AMR vector fields. These techniques have been implemented to augment the existing VisIt integral curve framework and will be deployed in a future release, allowing application of generic integral curve visualization without special considerations on AMR data.

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Scalable Integral Curves

The visualization techniques discussed in previous sections represent a significant step toward elucidating vector field visualization for many scientific problems. However, the insight provided by these methods comes at a high computational price. While geometric techniques such as integral surfaces require the computation of hundreds to thousands of integral curves, for Lagrangian visualization these number in the millions to billions. Each integral curve propagation requires many vector field

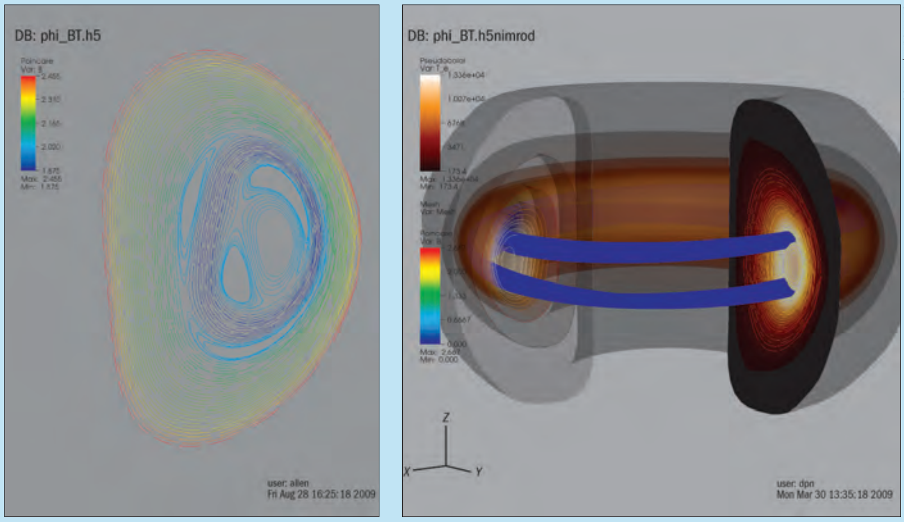
Visualizing Magnetically Confined Fusion

Fusion energy has the potential to provide an environmentally acceptable, virtually inexhaustible source of energy for the future. Fusion energy plants would harness the power that fuels the stars by fusing light elements within a hot plasma. Creating an environment amenable to fusion, where temperatures of 100 million degrees are required, is an enormous challenge. Tokomaks, such as the one being built by ITER, are fusion reactors that use toroidal magnetic fields to confine the burning plasma within the reactor core.

Simulations of magnetically confined fusion systems must model a variety of different plasma regions, including the core plasma, edge plasma, and the edge–wall interactions. Each region of the plasma is subject to anomalous transport driven by turbulence, which can lead to large-scale disruptions and instabilities. Many of these processes must be computed on short time and space scales, while the results of integrated modeling are needed for the whole device on long time scales. The mix of complexity and widely differing scales in integrated modeling result in a unique computational challenge.

One key area to understanding the behavior of the plasma is the topology of the magnetic field. An effective method for visualizing and understanding the magnetic field's topology is via a Poincaré map. This map is the intersection of a plane with the magnetic field and gives a cross-sectional view of the magnetic surfaces within the field. A Poincaré map is formed by intersecting multiple fieldlines, each of which lies on a magnetic surface, with a plane that is transverse to the magnetic field. As the fieldline traverses the field a series of puncture points will be accumulated. These points form the outline of the magnetic surfaces with the field.

Traditionally, forming a Poincaré map is computationally very expensive because in order to analyze the entire magnetic field, a large number of fieldlines must be considered. Further, each fieldline can require a large number (thousands) of puncture points to accurately outline each magnetic surface. To reduce this computational expense a new Poincaré analysis tool has recently been added to VisIt (figure 11).



S. Kruger, NERSC

Figure 11. *This new Poincaré analysis tool, developed by VACET researchers, uses the parallel streamline functionality to compute the magnetic field lines and then creates the Poincaré map using only a few hundred puncture points. The Poincaré tool is able to leverage the parallel streamlines in two ways. First, it enables analysis of simulations too large to fit into memory on a single compute node. Second, it allows a large number of field lines to be computed in parallel, irrespective of the size of the simulation. The ability to perform increasingly detailed analysis on a larger number of field lines on larger computational simulations is a powerful enabling tool for plasma fusion researchers. Simulation was performed by Scott Kruger using the NIMROD code on the IBM SP RS/6000 computer at the National Energy Research Center. Visualization and analysis were performed using VisIt.*

evaluations, which are typically expensive. Hence, the visualization of large data — or even of medium-sized data with many integral curves — with such methods mandates the use of parallel computation for acceptable performance and user experience.

The propagation of individual integral curves is mutually independent, and integrating many curves lends itself to parallelization. Based on this insight, a simple parallelization strategy statically distributes the set of seed points (each spawning one integral curve) over the available processors, with vector field data loaded on demand on each processor independently. This approach works well for small vector fields, because all processors have approximately the same workload, and hence parallel efficiency is good. In the case of large data, however, the performance of this approach strongly depends on the size and distribution of the seed point set. Some integral curves may traverse more parts of the data than others, requiring more time-consuming loading of data, while others finish propagating quickly, leaving their processors idle.

VACET researchers have investigated the benefits and problems inherent in static decomposition strategies and have developed a novel parallelization algorithm that aims at providing better efficiency of parallel resources.

A second approach distributes the entire vector field data statically among processors. Integral curve computation is then started on the processor that contains the seed point in its resident subset of the vector field and is passed to other processors depending on the course of the trajectory; that is, the computation follows the data. This procedure has the advantage of consolidating data loading at the beginning of the run, which removes a typical bottleneck from the computation. However, if the seed points are chosen such that only a small fraction of the domain is traversed, only a small subset of processors participates in the computation, resulting in suboptimal efficiency.

Overall, it can be observed that static decomposition of the seed set, the data, or both does not perform efficiently over the typical range of use cases presented by integration-based visualization. VACET researchers have investigated the benefits and problems inherent in static decomposition strategies and have developed a novel parallelization algorithm that aims at providing better efficiency of parallel resources. Rather than decompose statically, the algorithm performs dynamic distribution of both seed points and data parts to individual processors. To achieve this, one processor acts as a master and assigns other processors (slaves) data parts to load and integral curves to propagate. The master maintains an overview of which data parts are resident on the individual processors and how much work in the form of integral curves is assigned to processors. Thus it can quickly identify if processors are idle and appropriately redistribute the workload more evenly by telling other processors to load corresponding data and assume some parts of the overall workload. The master derives these assignments from a set of heuristic rules that are designed to identify and avoid overloaded or idle processors and I/O bottlenecks. This hybrid master/slave algorithm avoids the worst cases of static parallelization strategies while retaining best-case comparable performance (figure 13, p20).

As a major advantage, this hybrid strategy alleviates the requirement that a visualization user choose a specific parallelization approach in response to specific data or visualization method characteristics. Rather, it delivers good performance for a wide range of cases, and thereby significantly reduces the barrier of entry to parallel vector field visualization; this makes it an ideal candidate for a general-purpose, robust end-user tool. Along with the discussed static distribution strategies, the hybrid approach has been implemented and deployed in the VisIt tool.

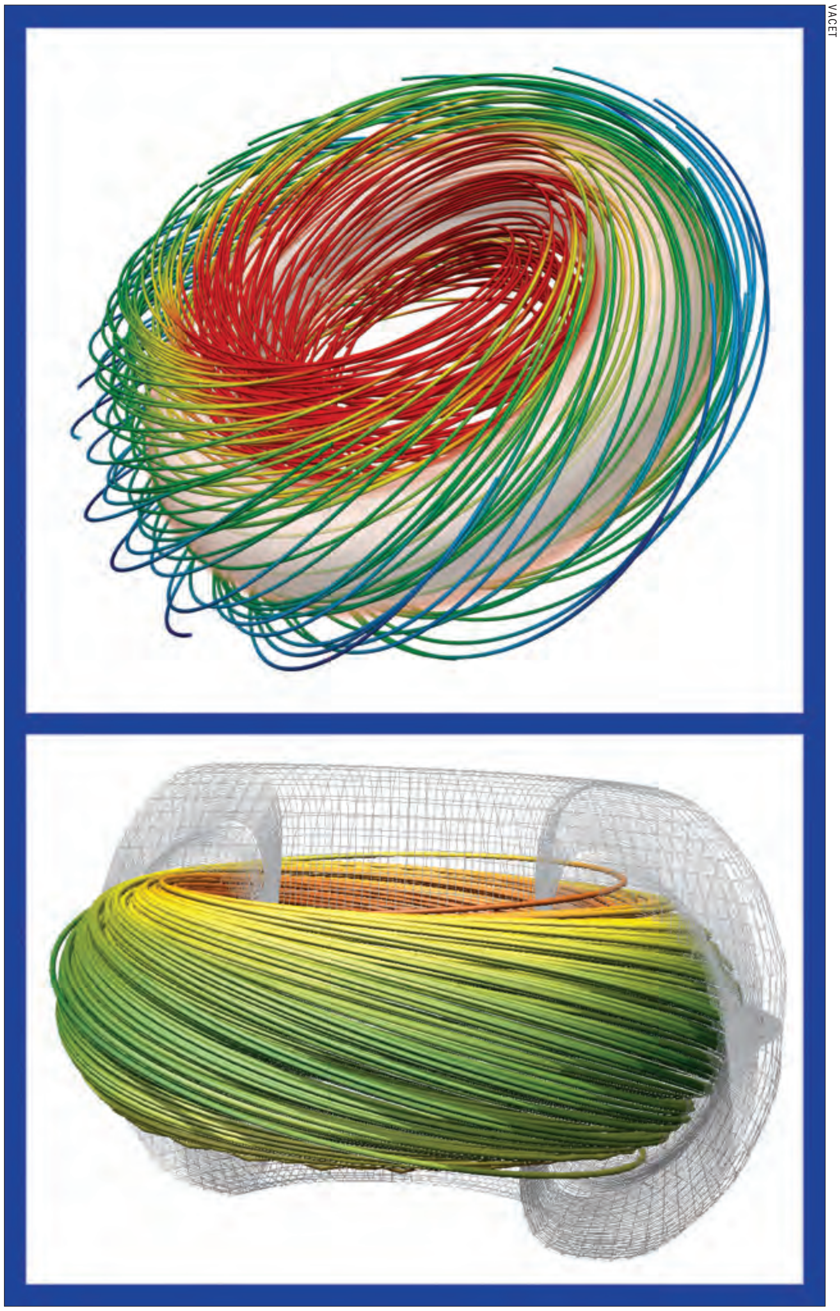


Figure 12. *Streamlines in a tokamak simulation.*

Vector Field Visualization Using VisIt

VisIt is an open source, turnkey application for large-scale simulated and experimental datasets. Its charter goes beyond pretty pictures; the application is an infrastructure for parallelized, general post-processing of extremely massive datasets. Target uses include data exploration, comparative analysis, visual debugging, quantitative analysis, and presentation graphics.

The VisIt product delivers the efforts of many software developers in a single package, leveraging several third party libraries: the Qt widget library for its user interface, the Python programming language for a command line interpreter, and the Visualization ToolKit (VTK) library for its data model and many of its visualization algorithms. In addition, an estimated 50 man-years of effort have been devoted to the development of VisIt itself. This effort has largely focused on parallelization for large datasets, user interface, implementing custom data analysis routines, addressing non-standard data models (such as AMR meshes and mixed materials zones), and creating a robust overall product. VisIt consists of over 1.5 million lines of code, and the third-party libraries have an additional million lines of code. It has been ported to Windows, OS X, and many UNIX variants, including AIX, IRIX, Solaris, Tru64, and, of course, Linux, including ports for

SOURCE: VACET ILLUSTRATION: A. TOVEY

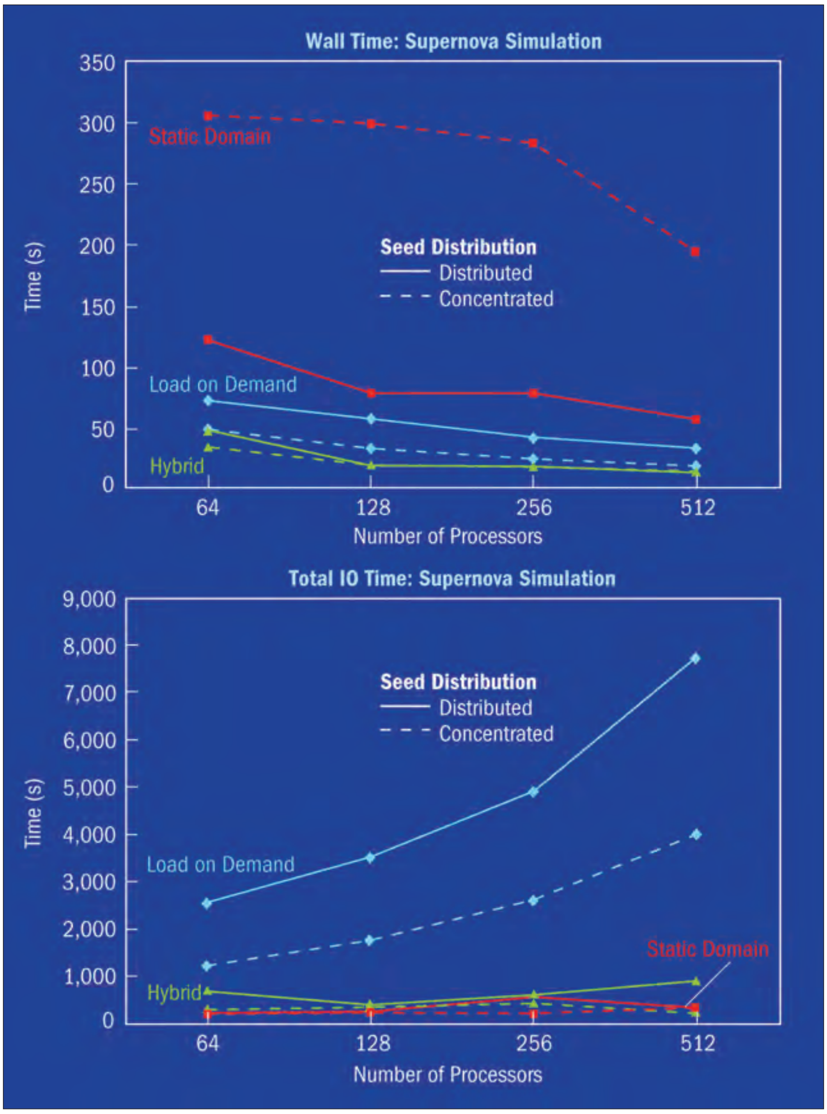


Figure 13. *Scalability results for computation time and I/O time of different parallelization strategies on a supernova simulation. The hybrid master/slave algorithm (green) retains the best-case characteristics of static decomposition with regard to data (red) and seed points (blue).*

VisIt received an R&D 100 award in 2005 and is downloaded approximately 50 thousand times per year. It is currently being used to visualize and analyze the hero runs on eight of the world's twelve fastest machines.

SGI's Altix, Cray's XT4 and XT5, and many commodity clusters.

The basic design is a client–server model, where the server is parallelized. The client–server aspect allows for effective visualization in a remote setting, while the parallelization of the server allows for the largest datasets to be processed reasonably interactively. The tool has been used to visualize many large datasets, including a 216 billion point structured grid, a one billion point particle simulation, and curvilinear, unstructured, and AMR meshes with hundreds of millions to billions of elements. Additionally, VisIt recently processed hero-sized synthetic datasets, ranging from one trillion to four trillion cells. Capabilities exist to link simulation code with VisIt to allow *in situ* visualization and analysis during a simulation run.

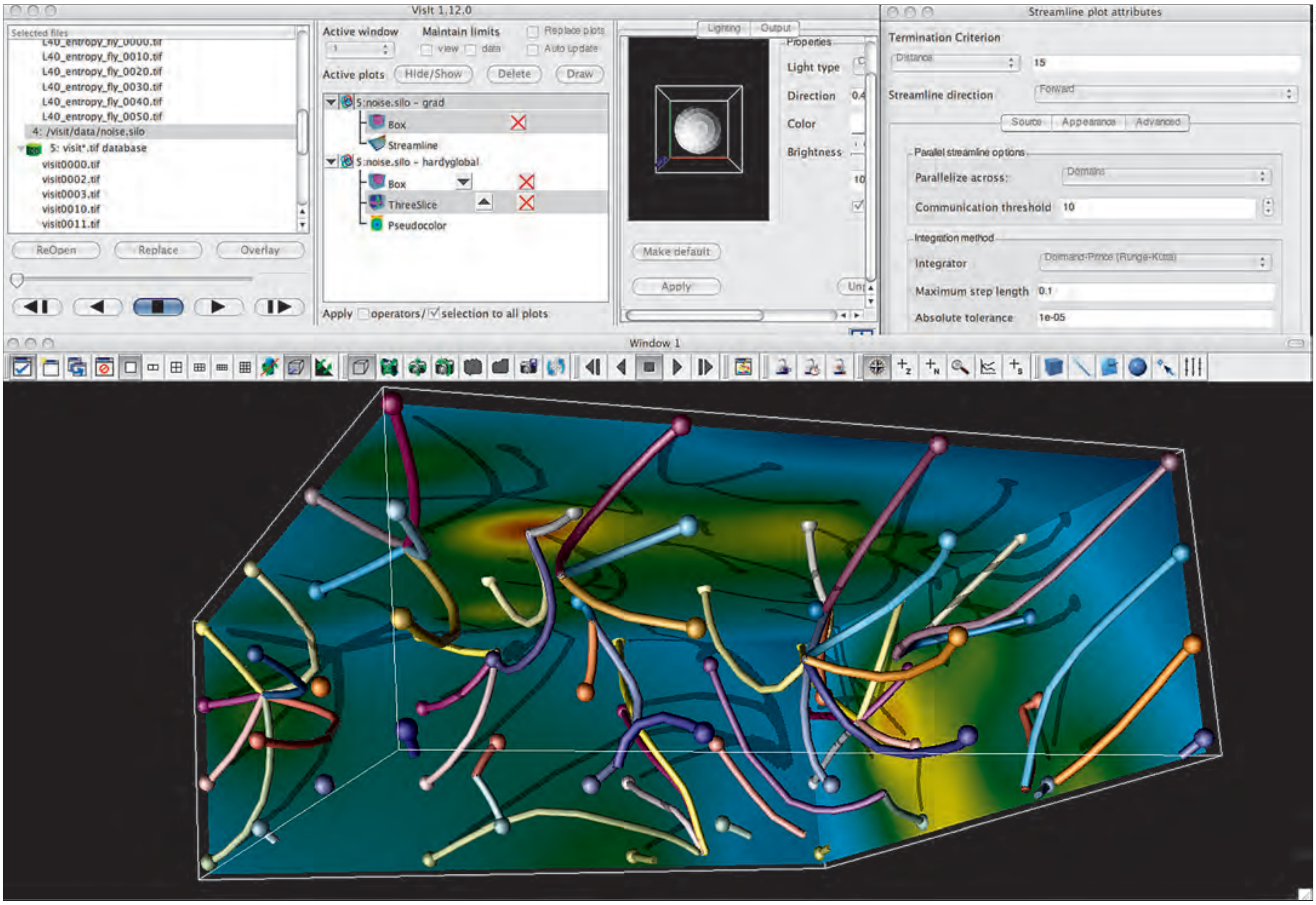
The VisIt project originated at Lawrence Livermore National Laboratory and currently has 25 developers from many organizations and universities, including five DOE laboratories. VisIt received an R&D 100 award in 2005 and is downloaded approximately 50 thousand times per year. It is currently being used to visualize and analyze the hero runs on eight of the world's twelve fastest machines.

Recently, VACET R&D activities have enhanced VisIt's capabilities toward vector field visualization, resulting in a modern framework for integral curve computation that enables out-of-the-box application of corresponding techniques on all supported data formats and mesh types. Using state-of-the-art numerical schemes, VisIt integral curve methods are applicable to the highly complex vector fields resulting from current- and next-generation simulations. In combination with VisIt's interaction and scripting capabilities that allow the interactive determination of seed sets and integration parameters, integration-based visualization is applicable over a wide range of use cases, ranging from rapid interactive exploratory visualization to high-fidelity presentation visualization.

As with most visualization algorithms in VisIt, the updated integration framework supports distributed computation to enable vector field visualization on large-scale data. It supports distributed data models and formats typically generated from corresponding simulations; hence, no data conversion is necessary prior to visualization. Furthermore, scalability is achieved through a choice of distributed computation paradigms that allows visualization users to maximize parallel efficiency for specific problem types. However, a newly-developed, hybrid approach automatically adapts to the problem characteristics in terms of data size and seed set distribution to achieve near-optimal parallel performance for a wide range of visualization problems. Users therefore are freed from having to choose a specific parallelization strategy.

From a software engineering perspective, the integration framework is designed with future visualization requirements in mind. It allows fine-grained access at different levels of complexity, which facilitates the development of novel visualization techniques, as well as the customization of existing algorithms with comparatively little effort. Leveraging VisIt's existing development infrastructure further simplifies this process. For example, a third-party library for Poincaré analysis for fusion visualization is easily incorporated into the existing infrastructure.

In the current release, VisIt offers basic capabilities for integral curve visualization using streamlines and pathlines, and advanced capabilities for Poincaré analysis. Integral surface support and Lagrangian analysis methods such as FTLEs will



VACET

Figure 14. *VACET has deployed streamline techniques (serial and parallel) inside of VisIt, the popular visualization tool used heavily in the Office of Science. This image shows a screenshot of the VisIt user interface and the streamline interaction capabilities.*

be included in an upcoming release. Overall, the goal is to provide through VisIt a modern, robust, and widely applicable tool for vector field visualization applications and research.

Conclusion

Modern vector field visualization algorithms are key components of successful vector field visualization in scientific applications. VACET researchers have developed and implemented state-of-the-art vector visualization capabilities, based on integral curve methods. In deploying the resulting algorithms in the open-source VisIt visualization tool (figure 14), VACET provides a robust, stable, and scalable toolset for vector field visual data analysis within SciDAC. ●

Contributors Christoph Garth, Eduard Deines, and Kenneth I. Joy, all from the Institute for Data Analysis and Visualization at the University of California–Davis; E. Wes Bethel, Hank Childs, and Gunther Weber, all of the Visualization Group at LBNL; Sean Ahern and Dave Pugmire from ORNL; and Allen Sanderson and Chris Johnson at the Scientific Computing and Imaging Institute, University of Utah; all contributors are VACET collaborators

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Further Reading

VACET
http://www.vacet.org/

VisIt
https://wci.llnl.gov/codes/visit/