Report

of the 2^{nd} Dagstuhl Seminar on

Scientific Visualization

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Organized by

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One of the important themes being nurtured under the aegis of Scientific Visualization is the utilization of the broad bandwidth of the human sensory system in steering and interpreting complex processes and simulations involving voluminous data sets across diverse scientific disciplines. Since vision dominates our sensory input, strong efforts have been made to bring the power of mathematical abstraction and modeling to our eyes through the mediation of computer graphics. This interplay between various application areas and their specific problem solving visualization techniques has been emphasized in this seminar.

The second Dagstuhl Seminar on Scientific Visualization brought together researchers from USA (17), Germany (12), Great Britain (1), The Netherlands (4), France (1), Australia (1), Switzerland (1), and Russia (1). The Contributions reflected the heterogeneous structure of the parts of scientific visualization we decided to concentrate on. Presentations were given e. g. in flow visualization, visualization techniques in software development, volume visualization, medical imaging, and visualization of vector and tensor fields. The heterogeneity concerned the application as well as the methods by which the problems were attacked.

In contrast to usual conferences the atmosphere of Dagstuhl strongly supports the exchange of ideas. It was a pleasure to see the always well occupied audience and to follow the extensive and intensive discussions after the talks. The reuslts of this very successful seminar will be published in a book. The idea is not to produce a proccedings voulme but an edited book containing tutorial-like sections as well as recent original work.

Participants

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Visualizing 3D Velocity Files Near Contour Surfaces

Max Nelson, Roger Crawfis and Charles Grant

Vector field rendering is difficult in 3D because the vector icons overlap and hide each other. We propose four different techniques for visualizing vector fields only near contour surfaces. The first uses motion blurred particles in a thickened region near the surface. The second uses a voxel grid to contain integral curves of the vector field projected onto the surface. The third uses many anti-aliased lines near the surface in the vector field direction, and the fourth uses hairs sprouting normal to the surface and then bending in the vector field direction. All the methods use the graphics pipeline, allowing real time rotation and interaction, and the first two methods can animate the texture to move in the flow determined by the velocity field.

Visualization of Turbulent Flow

Andrea J. S. Hin
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The Netherlands

The line of simulations in fluid dynamics starts with a hydrodynamic simulation determining the (water) motion of the medium. A grid and boundary conditions are input for the simulation producing several data fields, such as velocity, pressure, density, ... The water motion described by the velocity is used by a dispersion model to determine the spreading of concentrations of matter released from sources.
By using data from the hydrodynamic simulation where a turbulence model is included we can find an expression for the motion of particles in a turbulent flow. We use the velocity and eddy-diffusivity data, in fact separated by the simulation, to integrate the data in the particle motion. The method uses random-walks and is implemented in a Particle Tracer. A Particle Renderer displays the fluctuating motions of particles in animations.
Considering the particle path data, obtained from the particle method explained above, as instationary particle distributions, we can use a volume renderer to display it as (time-dependent) nebulous concentration fields in animation. This volume method shows large-scale effects of turbulence, especially the mixing. To see the dynamics of turbulence inside these clouds, the particle method showing the erratic/random motion is more convenient!

Data Reduction for Use in Scientific Visualization and Particle Path Approximation Using Bernstein-Bézier Polynomials

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Reducing time-varying scientific data sets is extremely important as a preprocessing step (before performing any kind of scalar or vector field visualization). The reduction paradigm proposed is based on the extension of surface curvature to higher-dimensional manifolds. Regions with high curvature are identified and points in these regions are selected one-by-one until a certain error tolerance is satisfied.
Particle path generation for curvilinear grids can be reduced to the integration of a given vector field restricted to the path itself. Using quadrilinear interpolation and Bernstein-Bézier polynomials for the approximation of the path yields integral expressions of products of Bernstein polynomials which can be evaluated numerically stable and very elegantly.

Visualizing Software and Data

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Software is a huge industry producing the most complicated data-driven systems ever created. A limiting factor in building larger systems is understanding the complexity. To aid in this task, we have created some novel visualizations of software related databases including:

- Source code change history
- Dynamic program slices and code coverage
- The integrity constraint structure of related databases
- Resource usage on a compute server
- Email communication among a community of developers

Our research focuses on extracting the information latent in corporate databases so that it can be put to competitive advantage. We have developed guiding principles, a suite of examples, and a production capability for visualizing abstract databases.

Visualization Approach to the Study of Singularities on the World Sheets of Open Relativistic Strings

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A visualization approach to the study of the singularities on the world sheets of open relativistic strings is presented. It is known that the singularities play a significant role in the string theory. A study of the behaviour of singularities can lead to a new understanding of the nature of processes in particle physics.
World sheet of open relativistic string in 4D Minkowski space as a central physical object of visual study is considered. As it is shown the solution of string equations gives a simple receipt for the construction of a world sheet. A representation of a world sheet in the form of a frame that consists of 3D points calculated on some supporting curve is given.
Visualization is incorporated for the analysis of the shape of world sheet, the study of the behaviour of the singularities and for empiric hypothesises' verification. Arising specific visualization problems such as optimizing the processing of large amounts of initial data, finding the most suitable projection from 4D into 3D space, and choosing the best way to view/clip the parts of studying object are discussed. Various images of the world sheets of open relativistic strings in 3D and 4D space with the singularities of different types are constructed. The role of visualizations for the discovering new features of string dynamics and investigations of the complicated processes and phenomena in string theory is shown. The desirable ways of future research using computer animation are discussed.

Implicit Techniques for Fluid Flow Visualization

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An algorithm for the construction of 3D-objects for the visualization of 3D vector and tensor fields is presented, based on primitives coming from metaballs introduced by Blinn and the convolution surfaces of Bloomenthal and Shoemake.
Using these primitives we can render stream and timelines as well as corresponding surfaces. Critical points in the field show up to be no problem because of the amazing melting and splitting properties of the used representation. The potential fields provide a variety of possibilities to map local parameters or even tensor information in parallel to the overall global information. Rendering can be done with standard techniques like marching cubes, but for interactive working further investigations for faster rendering can be done.

Image Warping, Volume Warping, Volume Interpolation

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Warping and morphing of digital images have become very prominent in the last few years. These topics have quite interesting applications in the field of rasterized volume processing and visualization, too. For instance, 3D warping is necessary in matching multimodal imaging data. 2D morphing may be applied for purposes of interpolating intermediate slices in non-isotropically sampled tomographic image stacks.
For image warping, we present an approach applicable also to multidimensional rasterized data sets. It has two aspects, deformation and resampling. Deformation is performed by application of scattered data interpolation methods, having the advantage of arbitrarily locatable control points. Radial basis functions and natural neighbor interpolation are two scattered data interpolation methods that behave quite well in this application. For resampling, the algorithm of Wolberg and Boult is modified so that it can easily be transferred to arbitrary dimensions, and that sampling artifacts are held low. We particularly focus on efficient implementation.

Morphing is done by deformed cross-dissolving. Again we show how an efficient implementation of that can be achieved.

Interactive Craniofacial Surgery Planning based on Visualization and Simulation

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Conventional planning methods for craniofacial surgery are mostly two-dimensional and do not allow a realistic and accurate prediction of the postoperative appearance of the patient. We present the present status of a project that aims at a photorealistic visualization of the post appearance using modern methods of computer graphics. In our approach, we are combining the data from a 3D surface laser scanner with volume data from a computer tomograph. The two data sets are registered based on a segmentation of the skin from the CT using a linear regression procedure. The skull is segmented from the CT data using the marching cubes algorithms. We employ a polygon reduction algorithm to achieve a more compact representation of the surface data sets for interactive manipulation. Operations are simulated by cutting objects on the workstation interactively and moving them to their new desired positions. Currently, we are implementing the simulation of soft-tissue deformations. The accuracy of the prediction of the postoperative appearance will be evaluated for 30 patients as part of the project.

Representation and Visualization of Knowledge about Human Anatomy and Function

K. H. Höhne, A. Pommert, M. Riemer, T. Schiemann, R. Schubert, U. Tiede
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Representation of knowledge about complex spatial objects like in human anatomy is presently looked at from two different views. Image processing

and computer graphics on one hand allow for graphical exploration with high quality rendering, while it does not care about the corresponding descriptive knowledge (e. g. about structure and function of objects). Knowledge engineering on the other hand can provide complex formal descriptions without generally providing for spatial visualization.
However, for many applications such as 3D-anatomical atlases a combined representation of spatial and symbolic knowledge is mandatory. We have designed and implemented a data structure called "intelligent volume", that includes "label volumes" containing points to a semantic network model of human anatomy and function. On this basis 3D-interactive anatomical atlases may be generated which allow exploration by arbitrarily navigating in both the pictorial and the symbolic domain: Actually displayed images may be inquired as to their meaning or, interesting object aggregates may be visualized in 3D rendering. It turns out that the intelligent volume approach allows to generate or simulate all classical visual aids in anatomy: dissection, atlas, movies and even solid models.

An Environment for Computional Steering

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Computational Steering is the ultimate goal of interactive visualization: researchers change parameters of their simulation and immediately receive feedback on the effect. We present a general and flexible environment for computational steering. Within this environment a researcher can easily develop user interfaces and 2D visualizations: Direct manipulation is supported, the required changes of the simulation are minimal. The architecture of the environment is that of a central Data Manager, which takes care of data storage and event notification, with satellites around it that can be simulations, data manipulation tools, and input and output tools. A graphics tool is provided to define a user interface and to show visualizations. The central concept here is the use of Parametrized Graphics Objects: an interface is built up from graphics objects whose properties (geometry and colour) are functions of the data in the Data Manager.

Visualization of Solid Reaction-Diffusion Systems

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In 1952, the mathematician Alan Turing wrote a paper entitled "The Chemical Basis of Morphogenesis" that introduced the principle of reaction-diffusion. According to this principle, as chemicals diffuse through an array of cells and react with each other, large-scale stable features, based on chemical concentration, may emerge if the conditions are correct.
Recently, cellular automata have been used as a vehicle for modeling the dynamics of reaction-diffusion systems. Convenient for simulation on computers, cellular automata provide a basis from which to investigate certain applications of reaction-diffusion behaviour.
We use a cellular automaton-based reaction-diffusion system to generate textures for computer graphics applications. Previous research has used two-dimensional systems to apply textures to the surface of objects; here, the model is extended to three dimensions. Thus objects may intersect a solid textural field, which permits effective solid textures to be created and rendered.
We begin with an analysis of cellular automata, and follow with the visualization of three-dimensional reaction-diffusion systems. A powerful, interactive environment is used to develop the cellular automata and reaction-diffusion systems. Volume visualization and isosurface rendering are two of the techniques used to comprehend the structure of the three-dimensional reaction-diffusion data.

Visualization & Deformation of the Brain

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Part 1: A brief summary of our research is presented that involves visualizing and analyzing MRI and PET scans of the brain of multiple subjects. Applications include studies on learning disorders, emotional disorders and several others with doctors at Samaratin Medical Hospital. The overview discusses the problems involved in aligning, registering and displaying PET and MRI scans at the same time. These scans use different coordinate systems and MRI scans produce information of "structure", while PET scans yield information on "function". For group studies, it is necessary to deform each patient brain to a standard fixed brain, because brains have significantly different shapes.
Part 2: After first discussing radial basis scalar interpolants for functions of three variables, we note the simple generalization to volume deformations. Given landmark points in volume 1 (brain 1) and corresponding points in volume 2 ("standard brain"), we define a smooth warping of volume 1 that we then apply to the PET data also. A new approach is presented that preserves the plane separating the left and right sides of each brain.

Design of Visualization Environment for Distributed & Parallel Systems

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Visualization in Scientific computing requires more and more complex processing, usually obtained by assembling several elementary components. This is true not only for hardware, but also for software.
Hardware environments are today distributed for many reasons, the combination of various resources (number crunchers, graphic systems, database systems, ...) not always available at a single location, or computing power only achievable through multi-CPU systems (parallel compilers, workstations). In addititon, scientific projects are more and more obtained through cooperation between different teams at different locations, needing Computer Supported Cooperative Working Tools.
New visualization software are implemented as collections of different modules that can be assembled together in order to be customized to the user's

needs. One of the big issues, when using them in distributed environments is to handle data exchange between these elements and try to optimize it as much as possible, since the size of the problems currently running on supercomputer can generate Gigabytes of information.
New architectures for software environments, mainly based on the Data Flow Paradigm have to be found. One direction investigated at our computing department is based on a Shared Data Space Management System through which different software modules can exchange data without being explicitly interconnected. A Distributed Space Manager handles Distributed Partitioned Objects and manages circulation of parts of objects on a network in a transparent manner for the modules using them. This approaches enables not only applications to inheterogeneuos environments, but also offers an interesting possibility of automatic load-balancing between modules.

Visaulization of Vector Data in Fluid Dynamics

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Flows are essentially described by a vector quantity, namely by the velocity vector field. Visualization of such vector data, in particular in the 3D space time domain is a complex task, most likely to give rise to errors and misinterpretation. Known techniques such as streamribbons and wall shear lines were used to visualize a complex hypersonic flow field around a blunt fin/wedge geometry. Comparative visualization of alternative methods allows to explore the potential use or danger of selected visualization technology.
The decision whether a given technique may be considered useful or likely to lead to misinterpretations strongly depends on the intended message of the image or on the inquired properties of the data.
The use of alternative methods increases the awareness for the potential and for the possible pitfalls invoked with application of a given technique. Often users are well aware of limitations of their mathematical model vs. the physics, which should be described by the model. They are similarily well aware about the numerical inaccuracies in a simulation process or experimental noise in the data. However, after identifying features or properties in the discrete domain of the data, discrete nature of the resulting visualization beyond the numerical inaccuracies is often neglected. The appearance of objects in images strongly depends on the discrete nature of the data, the data post-processing algorithm and last but not least on the visualization method chosen.
Comparative visualization of alternative methods may help in all respects of

the process.
A second useful application of such comparative visualization may be found when comparing data from different data sources such as experiments and according simulations. This is demonstrated in a case study of detecting discrepancies in the near wall representation of the hypersonic blunt fin/wedge flow field.

Tetrahedrizations

Gregory M. Nielson

Applications in scientific visualization which involve irregular, structured or scattered data require decompositions of the domain into a collection of tetrahedra. After an introduction to triangulation basics we survey some results to 3D which include a discussion of various algorithms for constructing tetrahedrizations, the problem and one particuar solution for affine invariance and data dependent tetrahedrizations.

A Lattice Theory of Data Display and its Application to Visualizing Scientific Computations

William L. Hibbard

Computer data objects are generally finite approximations to mathematical objects, and computer generated displays are finite approximations to idealized displays (i.e. real displays have finite resolutions of pixel locations, colors, animation time, etc.). We define an order relation between data objects based on how precisely they approximate mathematical objects and use this to define a lattice of data objects. We define a similar lattice of displays. We define a visualization process as a mapping from a data lattice to a display lattice. We define expressiveness conditions on these functions, requiring that displays exactly encode the information content of data objects. We show that a visualization function satisfies these conditions if and only if it is a lattice isomorphism. We apply this to particular lattices suitable for scientific data and their displays and show how to characterize display functions that satisfy the expressiveness conditions. These things are implemented in our VIS-AD system.

Visualization is information precessing

Heinrich Vollmers
DLR-Göttingen

The growing amount of information from numerical and experimental simulation in fluid mechanics must be effectively reduced and structured. Visualization is considered as a chain of information filtering to produce a meaningful representation of the data for using the broadest channel of information to

a human being. Several examples for analysis and representation of data, e. g. streak lines, time lines, vortex detection, was given and the analysis and graphic system comodi introduced. An outline of some more capabilities are given.
Discussing the instationary flow around a sphere (4D) and oscillating airfoil (3D) possibilities of topological and graphical representations are demonstrated. The dynamics of these processes are illustrated by video scenes created from data of numerical and experimental simulations.

Towards Volume Rendering and Data Analysis in Wavelet Spaces

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Wavelets have approved to be a promising basis for compact data representation and approximation. A set of orthonormal basis functions spans the space of finite energy functions and is derived just by scaling and translation of one prototype. Discrete Wavelets transforms can be implemented by QMF- Polynomials and easily be extended to multiple dimensions.
Since the WT is both located in the spatial and frequency domains, it can be employed to derive local features in data sets. Furthermore, based on given continuous wavelet functions, any data set can be approximated and expanded rejecting low-energy coefficients during the reconstruction, we get a data coding scheme in given error bounds along with the property of locally adaptive approximation.
This contribution first introduces to the theory of Wavelet transforms and compasses different types of wavelets. Secondly, its application as a feature extractor for unique texture analysis is illustrated and results on natural textures are presented. Extending this concept to 3D and approximating the wavelets basis with cubic splines, an analytic formulation of the very intensity function can be set up. This allows an approximate solution of the volume rendering equation. Thus, a unique data representation is postulated that allows both volume data analysis and rendering.

Cooperative Working Method for the Visualization of Supercomputer Simulations

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Scientific Visualization should be regarded as a part of the overall process of handling scientific or technical problems on the computer. For direct interaction with all processing steps and steering of the simulation, a homogeneous data model, data representation and execution model should be applied.
The architectural model and implementation of a cooperative visualization and simulation environment called COVISE is presented, which allows a flexible distribution of all processing steps such as simulation, filtering, mapping and rendering across supercomputers and workstations. Cooperative working functionalities such as simultaneous display of identical user interface and visualization state are part of CONVISE.
They are supported by audio-/video conferencing integration and telepointers. The described architecture differentiates from existing visualization packages by separate communication channels for data and control flow, persistence of data objects, optimized usage of high performance computers and networks.

Data Reduction and a Flow Visualization Technique for Layered Ocean Models

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Dynamic ocean models are now able to resolve dynamic meso-scale features such as eddies, but exact replication of observed oceanography remains an elusive goal. Typical datasets are on the order of 3 GB/year with 3.05 day temporal resolution and 1/8¡ spatial resolution. Analyzing the wide range of time and space scales is a demanding 4D visualization problem. To visually analyze such temporally varying information on existing workstations necessitates a hierarchical approach. A hierarchical, progressive scheme using biorthonormal wavelets is introduced. The technique allows visualization of long sequences and long-term synoptic information interactively, while allowing lossless visualization when desired.
Secondly, visualization of long-term (multi-year) synoptic information begged for a better synoptic flow visualization technique. Thus for mapping flow direction to hue and redundantly mapping flow magnitude to saturation and value has shown great promise.

Concepts for Interactive Visualization of Huge Data Fields

Wolfgang Krüger
GMD-VMSD

Currently new classes of huge data fields appear in supercomputer simulations and large scale measurements. For example, in CFD or FEM calculations field values on grids with $10^6 - 10^7$ vertices are calculated for each time step, or measuements in confocal microscopy extract about 1 GB/time step of data. Those huge data sets have to be visualized interactively with high fidelity rendering methods to support the data analysis process and the steering of the simulation. This visualization has to be done on the supercomputer itself or in a distributed environment linked together via a broadband net.
The talk addresses the special problem of interactive visualization of huge volumetric data fields via the transport theory approach. This method has been developed to provide a general mathematical model for generating high quality images with all necessary detail of interesting features. The transport theory appears to be a linear integral equation for the image intensity. This equation can easily be discretized and solved by matrix inversion methods.
The "classic" matrix inversion routines have $O(N^2)$ complexity and can be applied, e.g. via packages on supercomputers or iterative approximations on workstations, as long as the number N of the matrix rows is of order $10^4 - 10^5$. For monster matrices ($N > 10^6$) only modern optimal solution schemes of $O(N)$ can be used. Essentially, these methods transfer the original matrix into a sparse matrix, and provide some hierarchical approximation scheme.
For volume rendering two methods are proposed. The rendering and storage on hierarchical compressed data, e.g. by wavelet transformation, seems to be most promising. This method guarantees high compression rates with well defined error bounds, and data feature extraction methods can be incorporated easily. Another method to render complex scenes or large volumetric data is based on perturbation theory. From known solutions slight global or strong local distortions can be calculated very fast. This method applies especially for environmental radiosity problems or smooth time developments of volumetric data fields.

Visualization of Collision Detection Algorithms in Complex Polygonal Environments

Alfred Schmitt, Kurt Saar
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Collision detection and collision avoidance is an important and critical task in many Computer Graphics Applications. Major application areas are in Computer Animation, Robotics, Kinematic and dynamic Multibody System

Simulation, CAD and even in free form surface intersection. Our approach to collision detection is related to applications in computer animation, especially in the animation of simulated human bodies or actors. I our case, a number of parts or bodies are given and they are moved on a frame by frame basis on the time axis. The parts are normally complex polyhedral objects (volumes) whose surface is composed of many triangles, sometimes up to 2000. Our solution to the collision detection problem is straightforward but nevertheless very fast. We are using on the first level bounding spheres, on a finer level of approximation simple bounding volumes and on the third and finest level the triangular faces representing the surfaces of objects. The algorithm finds intersections in a systematic manner in first trying to find intersection on bounding volumes.

The algorithm was implemented on an Indigo Extreme and is reasonably fast to allow interactive work. Fine tuning is still in progress so that final results will be presented in the future.

Feature Extraction Tracking and Visualization

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Visualization is the process of converting a set of numbers resulting from numerical simulations or experiments into a graphical representation. However, the ultimate goal is to understand the underlying science. An essential part of visualizating massive time-dependent data sets is to identify, quantify and track important regions and structures. This is true for almost all disciplines since the crux of understanding the original simulation, experiment or observation is the study of the evolution of the features present. Some well known examples include tracking the progression of a storm, the change in the ozone hole, or the movement of vortices shed by the meandering Gulf stream.

In this presentation, we discuss techniques to isolate basic features and track evolving regions. These results can enhance visualization by highlighting areas of activity and reducing "visual clutter". Furthermore, it provides a mechanism for data reduction by abstracting out the essential dynamics and representing the evolution in a compact format.

Topics in Vector Field and Flow Visualization

Frits Post
Delft University of Technology, The Netherlands

The two topics covered in this presentation are a comparative analysis of particle tracing algorithms in curvilinear grids and visualization for comparative data analysis. The unifying theme is ensuring accuracy and validity of both the simulation and visualization stages.

Standard particle tracing is based on stepwise integration of a velocity field. Important components of the algorithms are point locaction, interpolation, and integration. We have investigated algorithms operating in the curvilinear grid in the physical domain, and in a Cartesian grid in computational space as used in CDF for solving the flow equations. The local domain transformation to map physical to computational space is the determining factor for accuracy and speed. If the vector field is given in physical space, the physical space algorithms are superior in both respects. (This work was done with Ari Sadaijoen, Theo van Walsum, and Andrea Hin at TU Delft and Delft Hydraulics).

Comparative visualization is the creation of visual images for comparison of different data sets. An obvious application is comparing experimented and simulated data for validation of simulation models. Two approaches with variants are presented: image level and data level comparison. Image level uses a separate pipeline for each data source, presenting images in a closely comparable or combined format. Data level uses a common data representation that can be processed by a single visualization pipeline. We show several examples taken from fluid dynamics. (This work was done with Hans Georg Pagendarm of DLR in Göttingen).

Incorporating Intelligence in the Design of Visualizations

Philip K. Robertson
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We present an approach to intelligent design of visualizations to allow flexibility between full user control and full automation. The approach uses metavisualizations - visualizations of metadata associated with the data and its mapping into visual attributes of a display - to provide the user with a clear path to exercising or relinquishing control over the choice of data mappings in an adaptive manner. We illustrate this approach with a colour management system that allows the mapping of data into perceptual dimensions of a uniform colour space. The system provides the tools for user control over mappings in a manner only constrained by the user-interface to the metavisualizations. We conclude that focusing on metavisualizations as well-defined functional units whose interactions with user, display and data models can be specified allows an incremental approach to incorporating intelligence in the design of visualizations.

Selective Visualization

Theo van Walsum
Delft University of Technology, The Netherlands

One of the problems in scientific visualization is that the amount of data is too large to be projected to the screen directly. Several methods have been developed to filter out information from the dataset before the visualization. In this presentation, I presented an approach to selective vector field visualization. This selective visualization approach consists of three stages: selection creation, selection processing and selective visualization mapping. It is described how selections can be represented and created, how selections can be processed and how they can be used in the visualization mapping. Combination of these techniques with a standard visualization pipeline improves the visualization process and offers new visualization possibilities. Examples of selective visualization of fluid flow datasets are provided.

Multi-Resolution Representation of Very Large Data Sets for Interactive Visualization

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Modern scientific research techniques are generating increasingly large amounts of data. Although the interpretation of this data can sometimes be automated, most of the time it is necessary for a human to visualize the data in order to discover its inherent information. The visualization of huge data sets is normally done at different levels of scale and resolution. A scientist usually needs to see a large scale view of the data (at low resolution, because of display limitations) in order to identify regions of potential interest. Then, the scientist "zooms in" to the region of interest in order to see a higher resolution view (of smaller range). This process may then be repeated to several levels.
This research addresses the storage and retrieval of large data sets in a hierarchical multi-resolution form. The goal is to trade-off space and time for the storage and retrieval of the data, while also maintaining knowledge of, and control over the error introduced by the low resolution representations of the data. We describe a prototype system that represents a data hierarchy based on wavelet transforms. By using a wavelet transform that is invertible and orthogonal, we produce coefficients which are highly localized in both the space and frequency domains. A user can see regions of the data that have significant characteristics by looking at the coarse approximations of the data, but can still "zoom in" to see fine details. The fast and accurate decomposition and reconstruction of wavelet transforms make them an efficient mechanism for browsing very large data sets at different resolutions.

Scientific Visualization in Massively Parallel Computational Environments: Fast Parallel Rendering

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In recent years, massively parallel processors (MPPs) have proven to be a valuable tool for performing scientific computation. Environments composed of MPPs, Massively Parallel Computational Environments, prove to be both a blessing and a curse. The finer grid resolution possible in these environments allow for better simulation of the underlying physics. However, the finer grids also cause a data explosion. As the resolution of simulation models increases, scientific visualization algorithms which take advantage of the large memory and parallelism of these architectures are becoming increasingly important. The huge amount of data produced impedes distributed visualization due to the lack of available network bandwidth, storage systems and data management. Furthermore if one wishes to monitor or steer simulations, a tight coupling of visualization, in particular the rendering, with the simulation is necessary. Obviously, if the time to render an image is larger than the time to compute a timestep then it is impossible to steer and infeasible to monitor such simulations.
One approach to this problem is to visualize the data in situ on the MPP where the data is generated. We describe our experiences with a scalable data parallel, sort-last, polygon rendering technique which achieves, or exceeds, rendering speeds of current state of the art graphics workstations. One of the goals of this research is to develop a rendering algorithm which is efficient for large numbers of polygons (greater than 1M polygons). For such large polygon sets, we make the assumption that most of the polygons will cover a relatively small number of pixels since scientific datasets tend to produce such polygons. As we will show, image generation time is much less than that required by direct volume rendering and network traffic is reduced to transferring the image rather than the dataset.
Additionally, this model extends the usefulness of visualization environments, such as AVS or Explorer, because the user can decide at runtime whether to perform the rendering on the workstation or on the MPP. Another benefit of this approach is the capability of directly calling rendering functions from the running computational model. This not only allows for simulation monitoring/steering but also has proven to be an extremely useful tool in the debugging process.

VolVis: A Volume Visualization Testbed System

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A comprehensive volume visualization software system, VolVis, is described. VolVis is a diversified, easy to use, extensible, high performance, and portable system, that provides a flexible tool for scientists and engineers as well as for visualization developers and researchers. VolVis accepts as input tree-dimensional scalar and vector volumetric data as well as 3D volume sampled geometric data. The geometric data is either point-sampled (binary data) or volume-sampled. Interaction with the data is controlled by a variety of 3D input devices in an input device independent environment. VolVis output involves static images, navigation preview, and animation sequences. A variety of volume rendering algorithms are supported, ranging from fast rough approximations using hierarchical representation, to Fourier compression-domain volume rendering, to accurate volumetric ray tracing and radiosity, and irregular grid rendering.

Visualization of Vector and Tensor Datasets

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We consider visualization mappings of vector and tensor datasets from the viewpoint of representation theory. The discussion provides a theoretical basis and a unified framework for analyzing diverse vector and tensor mappings. To be effective, visualization mappings must extract physiologically meaningful representation from the data. A broad classification can be made according to the information level that is represented (elementary, local, global) and the domain over which the mappings are defined (point, line, surface or volume). For vector datasets we have developed topological representations that provide global information about a flow field in a compact and simple manner, yet retaining all pertinent information. Similarly we have analyzed tensor datasets. In general it can be shown that a second order tensor can be decomposed into a symmetric tensor and a vector field. For symmetric tensors we developed the concept of hyperstreamlines to visualize the eigenvectors using a line icon approach. By analyzing degenerate points (where two eigenvalues are the same) a topological representation can be synthesized that reveals important tension properties in a simplified, yet powerful manner while retaining all pertinent tensor data information.

Visualizing Streaklines of Large-Scale 3D Time-Dependent Flow Fields

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In numerical unsteady flow simulations, it is very common to generate several thousand time steps of flow data. Each time step may require tens to hundreds of megabytes of disk space. Interactive visualization of this large-scale unsteady flow data set is nearly impossible due to the current hardware technology. A subset of the flow data is sometimes generated so that the subset can fit into the physical memory of the system, and thus allow interactive visualization. The subset of the data can be generated by subsampling the data in the spatial domain. However, the data subset generated using this approach may not accurately represent the flow data. For streaklines, it is necessary to advect particles through the flow field using all the time steps of the data. A particle tracing system called the Unsteady Flow Analysis Toolkit (UFAT) was developed to visualize streaklines using a large number of time steps of the data. Streaklines show time-varying phenomena that are sometimes difficult or impossible to see using instantaneous visualization techniques such as streamlines and color contoured surfaces.

Virtual Reality Experiments in Scientific Visualization

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Virtual Environments represent a powerful, novel way in Man Machine Interaction. Scientific Visualization copes with large amounts of numbers which are often very hard to interpret. The availability of Virtual Environment (VE) techniques — immersive presentation of simulation results and direct manipulation — has initiated the discussions about the benefits of VEs in Scientific Visualization and has let to a number of experiments in recent years.

The strength and the weakness of VE techniques were discussed with respect to Scientific Visualization. Examples of direct manipulation in general purpose visualization systems and in arthroscopic training simulation were

presented. Visualization examples showing results from room acoustic simulation and interior light simulation were shown and discussed.
As a conclusion, VE techniques today are really in an experimental phase in Scientific Visualization, due to incompatibility with existing user interfaces, lack of technology and powerful systems.

Adaptive Data Approximation using Hierarchical Triangulations

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We consider the problem of approximating a set of data points $(x_i, y_i, f(x_i, y_i))$ by a hierarchical sequence of triangulations. A Voronoi diagram based cluster analysis method is proposed to generate both a set of knot points (cluster center points) and their Delaunay triangulation. We introduce the dynamic operations insertion, deletion and moving a point in a Delaunay triangulation to perform the clustering algorithm directly onto the triangulation. That way the corresponding Voronoi diagram could be used to enhance the algorithm significantly. Starting with one cluster, the cluster with the largest error is subdivided into two. The following k-means iteration onto all changed clusters ensures a local minimum of the cost function (trace of the within group scatterer matrix) after each step. Thus a hierarchy of triangulations is generated up to the triangulation of all data points (with error zero). In order to obtain better results we propose data dependent triangulations which yields a much better approximation once the knot points are fixed by the method described above.

Preserving Shape in Scientific Visualization

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In scientific visualization, when the data is known only on a coarse grid, we rely on interpolation to “fill in” between the data points. This is essentially the process of creating an empirical model to represent the “reality” from which the data has been sampled.
Often, however, we know additional “physical” information about the shape of the model — for example, concentration of chemicals in a reaction will be always positive. The aim of shape preserving interpolation is to preserve

these additional properties.
We explain how positivity can be preserved for:

- 1D - by adding extra knots in piecewise cubic interpolation
- 2D - by projecting if necessary the derivatives at grid points before calculating the bicubic interpolant or using a Gordon blending method from a curve network.
- 3D - by extending the blending to a 3^{rd} dimension

Finally, we note that a transformation to log space can preserve positivity automatically.

Visualization of Deformation Tensor Fields

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Scientific Visualization is a new approach in the area of simulation. It allows researchers to observe the results of simulations using complex graphical representations. Visualization provides a method for seeing what is not normally visible, e.g. torsion forces inside a body, wind against a wall, heat conduction, flows, plasmas, earth quake mechanism, molecules, etc.
Vector- and Tensor fields are very important in many application areas. The purpose of this talk is to present new techniques to visualize deformation tensor fields and infinitesimal bendings.
A deformation tensor is symmetric. We use the real eigenvectors of this symmetric tensor to display characteristic curves on the surface and as an alternative use the eigenvalues as interrogation functions in a focal analysis interrogation.
Considering infinitesimal bendings we introduce an "associated" vectorfield and construct an instability surface. The area of this surface is used as a "visible measure" of the deformation tensor field.