Visualizing Data: Focusing on an Approach

The very abundance of visualization techniques can make selecting the one most appropriate for bringing out the meaning in data a perplexing search - a difficult, frustrating, and time-consuming aspect of visualization. If your thought process is like ours, you most likely rely first on experience. If nothing appropriate suggests itself, you may turn to other convenient sources: programs that colleagues are currently using or a new technique a friendly programmer offers. In each instance, you study the resulting image for any useful information it may reveal. This reflexive "try, then study" approach may eventually yield an image that reveals the meaning in the data, but it is just as likely to yield an image that is pretty but useless.

A methodology is needed for selecting visualization techniques, but the nascent discipline of scientific visualization does not yet have pat formulas for selecting appropriate techniques. A focused approach like that outlined in the following paragraphs is one we have found successful. It is meant to eliminate obstacles that may obscure valuable techniques.

In describing this approach, we have sometimes used a broad brush to depict a complex subject. Wherever we introduce a simplified view, we also refer you to texts with more detailed discussion. Our goal in simplifying is to quickly put an image of your data in your hands by shielding you from detail while building your under≠standing of scientific visualization.

The main points in our approach are to:

• Identify the visualization goal: We identify the meaning we seek in the data before we begin to construct an image. Knowing the goal, we may recognize new sources of techniques; meanwhile we have a focus for determining if a prospective technique is likely to reveal the meaning.

• Remove mental roadblocks: We regard data as nothing more than numbers bearing information to be visualized. When we think of data as belonging to some application or having some structure, we unnecessarily limit ourselves in imagining possible techniques.

• Decide between data or phenomena: We distinguish between data-representation and contextual-cue techniques. Data representation shows the data values indepen≠dent of the phenomenon; the viewer must deduce the relationship to the phenom≠enon. Contextual-cue techniques relate the data values to the phenomenon being studied and add meaning to the visualization. Deciding whether data or phenom≠ena are the focus further refines the visualization goal.

Identifying The Visualization Goal

Beginning data visualization by first identifying the visualization goal may give some pause, but we believe identifying the goal is the cornerstone in constructing an effective image. The goal is the meaning you hope to derive from the image, and, if appropriate, the meaning you want to communicate to others about your data.

Identifying what you want to learn helps you select techniques that will produce an image communicating that meaning if the data support it. Just as a builder must know the building plan to select the correct construction materials, so too should you identify the desired result before proceeding to select techniques for visualizing data.

Usually data visualization consists of exploration, analysis, and then presenta-≠tion - if the visualization is used to communicate with others.* Identifying the ultimate visualization goal may be evolutionary, reflecting the stage in the visual≠ization process in which we are involved. Exploration, the searching of data for new relationships, usually means many trial-and-error data representations and requires interactive adjustment of data or image. Analysis, the study of known relationships among data, may require metrics or other precise means for comparison. Analysis and exploration are generally accomplished by one person or a few, and images that result need not be pretty or refined; they may even be unlabeled and, hence, meaningless to someone not familiar with the data or problem. Presentation is the "publication" of data for the benefit of others; the image should be aesthetically appealing, properly annotated, and intelligible.

How do you identify a visualization goal? Regardless of where you are in the visualization process, you need to ask such questions as Why am I looking at these data? What is important about the data? Am I comparing, associating, locating, verifying, finding, ranking, searching? What do I hope to learn? What do I want the image to say? What do the data prove? What do I expect the data to prove? In the exploration stage, the goal may be less focused than in the analysis and presenta≠tion stages. See Appendixes A and B for possible goals.

In fact, you are already identifying visualization goals, though perhaps subcon≠sciously, when you input data to a graphics utility you have used for similar data. The unstated goal may be, "Compare this image with the prior image." Or this idea might be at the back of your mind, "If it is wrong, I will know it," meaning, "Verify the correctness," or again, "Compare this image with the correct image." The more you can focus the goal, however, the more effectively you can construct images. 11-1 provides a good example of how the visualization goal affects technique selection. Both images are constructed from the same data, but because each image uses a different color palette, each depicts different information. In 11-1, Figure A, the goal may have been "reveal shape," and in 11-1, Figure B, the goal may have been 61 examine structure." Identifying the goal permits the selection of the appropriate color palette. The more specific the goal, the better focused and more useful the visualization.

Removing Mental Roadblocks

Here again, we suggest an approach that may seem untraditional. Our experience with scientists and engineers leads us to believe that many have been conditioned to regard data as some entity with inviolate properties. This rigid thinking may

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- Some visualization specialists distinguish types of visualizations by the terms *personal, peer*, or *presentation*. We prefer to distinguish types of visualization by the terms *exploration, analysis*, and *presentation*, which emphasize the functional aspects of visualization

Other algorithms that convert or modify data take randomly positioned data and convert them to regularly positioned data, minimize noisy data with smoothing algorithms, or create planar data by passing a plane through a volume of data.

You can find algorithms for data conversion in numerical analysis and computer graphics journals. Also, each of these four books describes a few conversion algorithms: Andrew S. Glassner, ed., Graphics Gems (San Diego: Academic Press, 1990); James Arvo, ed., Graphics Gems II (San Diego: Academic Press, 1991); David Kirk, ed., Graphics Gems III (San Diego: Academic Press, 1992); and William H. Press et al., Numerical Recipes (Cambridge, Eng.: Cambridge University Press, 1986).

We urge you not to hesitate to convert data to a different format or structure because you fear that conversion may introduce errors in approximation. Such errors, though harmful if the data are to be used for continued simulation, generally cannot be discerned in the data representation of an image. Ignoring conversion errors, especially in the exploration phase of visualization, encourages rapid evalu≠ation of techniques. Our experience shows that positional errors introduced are small and errors for data values even smaller. Whether these errors are tolerable depends, of course, on the application. An architect's plan for uniform air tempera≠ture in a small room is less critical than a surgeon's plan for risky, delicate surgery. Generally, though, errors are tolerable during exploration but must be accounted for in analysis.

Data conversion can be a complex, tedious issue that may have to be addressed for accurate analysis. But if you find a visualization algorithm you want to use, we suggest that you convert your data to the algorithm's input format and structure rather than rewrite visualization algorithms to work with the format or, worse yet, forgo constructing a meaningful image because you think your data cannot be used with the algorithm.

Eliminating Constraints of Dimension

Thinking that the representation's dimensions or number of variables must be the same as those in your data can also channel your thinking and eliminate useful techniques. For example, in selecting a representation technique you can often treat a 2-D scalar field and a (single-valued) 3-D surface as the same kind of data set. You can then use the same visual techniques for both kinds of data. 7-3 illustrates how a 2-D scalar field can be represented as a 3-D surface. Conversely, a 3-D surface can be projected on a plane and the values treated as 2-D, a technique commonly seen in U.S. Geological Survey maps, for which data on elevation are projected to a plane that is then represented as a contour map. With either data set, the 2-D representation can be a contour plot or pseudocolor plot, and the 3-D representa≠tion can be a shaded surface. The shaded surface could also include isolines and color.

Nor should the number of variables limit your representation choices. A variable is said to be a dependent if it is a function of another variable (called an independent variable). In the equation $y = f(x)$, x is the independent variable and y is the dependent variable. You can use the common x-y scatterplot to study the relation≠ship. If you have a two-variable data set x and y (say temperature and humidity), where x and y are measured at the same point, you have two variables. There is no defined relationship. You can visually determine if there is a relationship, though, by using the same x-y scatterplot as you used to show the relationship between the independent and dependent variables. In using a visualization technique, it often does not really matter whether you have two variables or one dependent variable and one independent variable. Whether it makes sense to choose the technique is another question, determined by what you are trying to learn from the image, not by the relationship between the variables.

Multivariate data can be especially challenging because of the many dimensions or variables. We illustrate several ways of handling multivariate data in the multiva≠riate category of Section II. Also, the dimensionality of multivariate data can sometimes be reduced by combining variables and then analyzing the data. **2-1** uses a three-variable technique effectively to analyze the relationship of four variables. On the other hand, data can be redundantly encoded to permit low-dimension data or data with a few variables to use a technique that requires higher-dimension data or more variables. **7-2** illustrates data redundantly encoded to height and color. An effective technique for handling multivariate data is to divide and conquer by representing each variable relative to another on a scatterplot. If random structures appear in some scatterplots, they may indicate a less important relationship between the variables. The variables related to the random-appearing scatterplots may be ignored for the moment, resulting in a lower-dimension data set to investigate.

Our aim is not to describe all possible ways of thinking about data, but to show that the same data set considered differently allows you to imagine different represen≠tations. The appropriateness of the representation will depend on the data.

Deciding Between Data or Phenomena

Techniques are the collection of rules, procedures, and algorithms whose system-atic application produce an image that communicates the meaning implicit in data. We distinguish between the data-representation techniques that represent the numeric values of data and the contextual-cue techniques that provide additional clarifying, interpretive meaning to the representation of the data.

Data-Representation Techniques

Data-representation techniques are those well-defined algorithms that take data as input and deliver an image as output. A simple example is the 2-D contouring algorithm, which takes a 2-D array of values and returns a set of isolines. Surface plots that show shape and texture; volumetric plots, which include a number of techniques that expose relationships in 3-D; *x-y* plots; scatterplots, histograms, and bar charts are other techniques for representing data.

Contextual-Cue Techniques

Visualization achieved by contextual-cue techniques is somewhat equivalent to the special effects with which photographers, artists, and moviemakers deliver mean≠ing to viewers. The cues may result from parameters in the computer program that control the output's appearance from a data-representation algorithm, or they may be the special effects introduced in the image by adding or removing other graphic elements. Contextual-cue techniques are usually applied apart from the data-representation algorithm; examples that suggest the properties of the phenomenon being studied are models, coastlines, motion blur, haze, hounding boxes, perspec≠tive, and color. The techniques can also make representations of data values and relationships more readable, such as numbered scales and grid lines that make values readable or the color, size, and position of abstract objects that suggest value and relationships.

Relating Data to Context

For an image to clearly communicate a visualization goal, you usually must incorporate both data-representation and contextual-cue techniques in an image. The need to distinguish between and to use both kinds of techniques brings to mind Hamming's statement:

The purpose of computing is insight, not numbers.

To provide insight you must do more than symbolically represent the numeric values of data; you must also relate those values to the phenomenon that the data represent. We offer the following simple example to show the additional insight commu≠nicated by using contextual cues that represent or identify the phenomenon.

Assume we have a 100 x 100 square array of numeric data values to examine. Pseudocoloring the values according to the visible light spectrum (blue, low; red, high) reveals a cluster of red that locates the maximum. Now we have an image that conveys the relative value of the numeric data. What does this cluster actually represent? The scientist studying the data values knows the cluster represents temperature measurements of a circuit board on which the components that are running too hot are to be identified and replaced. The meaning communicated by the image, however, is simply, “high values are located.”

If on the array of colors we use contextual-cue techniques to superimpose labeled, white, rectangular outlines representing individual components on the circuit board, the cluster of red now locates and identifies the hot component and the meaning becomes “hot circuit component identified.” We have changed our emphasis from relative values of the data to meaning of the data by also showing the phenomenon the data represent.

Initially in constructing an image, you may use only data-representation tech≠niques that visualize the numeric values of data. But for effective presentation to those unfamiliar with the data, an image that represents the phenomenon is a necessity. We also believe that even for those familiar with the data, a representa≠tion of a phenomenon is more valuable than a numeric representation. A phenom≠enon representation more clearly reveals the meaning and more accurately presents the information. **8-4** illustrates the increased meaning available in such a represen≠tation. In the figure, color depicts numeric values of a 2-D pressure field. Those familiar with the origin of the data know that a launched space shuttle creates the pressure field. But even for them, superimposing the context, the 3-D model of the shuttle, instantly shows the relationship of the pressure field to the shuttle configuration.

Representing Phenomena

When phenomenon is your focus, you should select techniques that create cues corresponding as closely as possible to the viewer’s experience with the phenom≠enon. Color, shape, texture, or setting may suggest the phenomenon: blue can suggest water, arrows can suggest projectiles. **2-13** and **7-8** choose color to suggest the properties of the phenomena being studied and to help the viewer draw conclusions. **10-8** applies color to suggest the planet Mars and photographer’s tricks to add the depth cues. The teacup in **10-4** provides the setting that indicates the fuzzy white objects are steam. **1-1** adds lines describing the shape of the world and its continents to bring meaning to the measured ozone data. The shape the data describe can also suggest meaning, as in **10-2**, where the viewer recognizes the shape as that of a backbone.

Choosing techniques to represent the phenomenon may require some creative or artistic talent, especially if the phenomenon is abstract or has never been seen, such as the inside of a proton, or a black hole. To illustrate such phenomena, you may add abstract cues to suggest the expected environment of the phenomenon, as in 6-3, where color represents the quark property and motion blur and position illustrate inter≠action in a phenomenon never seen.

Ideas for contextual cues may be found in art books, design books, television commercials, and, closer to home, in Edward R. Tufte’s Visual Display of Quantitative Information (Cheshire, CT: Graphics Press, 1983). The data-representation tech≠niques are usually found in graphics systems or graphics libraries, such as PV-Wave, AVS, Explorer, and NCAR Graphics. More recent data-representation techniques can be found in the Graphic Gems series previously cited in this section.

Constructing Ideal Images

The continuum of understandable visual techniques seems to reach from

> Instantly understandable to
> Takes some study time to
> Requires additional schooling.

The ultimate goal of visualization is to create complete images that "speak" to the viewer without additional explanation. To demonstrate what we mean when we say "speak," we ask you to recall computer-generated images or to thumb through the images in this book. Some will simply and clearly speak to you-you will understand the images immediately. Others will require some time to view and ponder, but then you will understand. And no matter how long you study some images, they will be no more than images-they will not speak to you. We realize immediate under≠standing may not always be attainable, but we believe you must have such a goal for each image Test the image (and by implication, you) communicate poorly or imprecisely, or not at all. We assert that the end purpose of an image is to facilitate communication of knowledge, not merely to display or represent data.

To understand the challenge of visualization, we compare art and scientific visual≠ization to show why visualization may be so difficult. Both have the goal of communicating visually and symbolically. The artist, in using such established tools as canvas, brushes, and oils to illustrate a point of view, benefits from the knowledge of centuries. The tools of scientific visualization-output device, data-conversion software, software to depict data - as well as the knowledge of how to use them are still evolving. The computer's power is needed to handle voluminous data, convert data, and apply visual techniques that reveal and communicate meaning hidden in data. The available computer tools, however, sometimes impair or limit ability to display data meaningfully or artistically. Scientific visualization is in its infancy. Computer artistry is a long way from representing data with the proficiency of a Michelangelo, Van Gogh, or Picasso.

Meaning and beauty are in the eye of the beholder. For any set of data, a spectrum of correct representations could accomplish the visualization goal, but even more representations would not. The correctness of a representation depends on your purpose. A complex, obscure representation might be quite adequate for personal use, but a general audience will need a simplified, obvious representation. Again, the goal for any representation is to make information about the data values or the phenomenon clear and immediately obvious to the viewer.

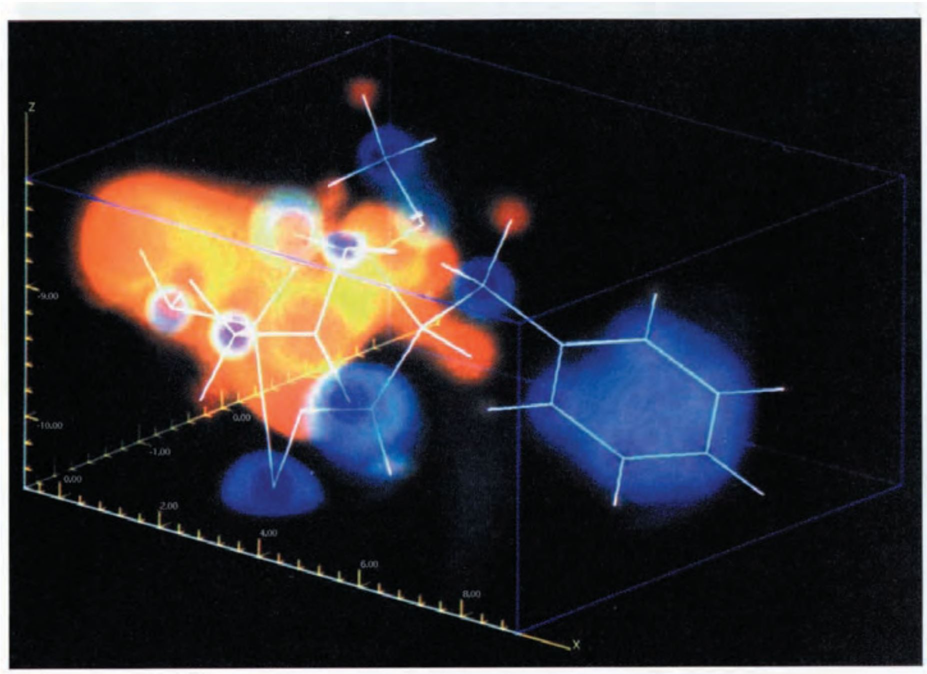
Conclusion

To facilitate constructing images that effectively communicate the meaning of the data, we advocate thinking of an image as comprising a visualization goal, one or more data sets, and a collection of techniques, each deliberately chosen to commu≠nicate the meaning that is in the data. The data are numbers that can be converted or transformed to be input to any representational technique.

Although we suggest not classifying data so that other data-representation tech≠niques can be considered, it is certainly possible that the best visualization is the one commonly used with those data. The best solutions to problems in data visualization result from considering the possibilities and selecting the most appropriate. And if the familiar technique best communicates the meaning of the data, then it is the most appropriate. If you have a technique that works, by all means use it. Understanding is always the goal.

The relationship between the visualization goal and the choice of techniques for accomplishing that goal is just beginning to be understood. Appendix A lists generic visualization goals, suggests techniques to accomplish the goals, and points to examples from *Visual Cues* that depict the techniques. Appendix B formalizes the relationship between goal and technique by defining terminology to use in classi≠fying the goals.

Comparisons and Relationships 1-5



1 dependent variable
3 independent variables
Associates 3-D geometry and volume data
Computational Chemistry

3-D geometry rendered with volume data permits correlation.

Application (Molecular Modeling)

The electric-charge distribution of a NutraSweet molecule in a ~33 x ~22 x 68 volume of data and the 3-P chemical-bonds geometry are simulated by molecular modeling software’ on a supercomputer. The image was rendered on a Silicon Graphics IRIS workstation using VoxelView®/ULTRA.

Technique

Embedding traditional geometric graphics (lines in this case) in a 3-P volume provides the accuracy of the geometric positioning with the information content of the volume rendering. The pseudocolored cloudlike features represent the charge distribution. Numbered axes provide a mechanism for approximating the size of the features. The perspective bounding box provides the cue to read the molecule as a 3-P representation.

Hints

Interactive control of volume translucency permits shifting of the focus between the volume data and the geometry data.

Vincent Argin, Vital Images, Inc., Fairfield, IA, USA; submitted by Maggie Vancik, Vital Images, Inc.

[1] Data courtesy of Gary Griffin, using molecular modeling software from BIOSYM Technologies, Inc.

Time 3-9

1 dependent variable
3 independent variables.
Depicts flow
Visualization

Topological surfaces depict time history of 2-D flow.

James L. Helman and Lambertus Hesselink,Stanford University, Stanford, CA, USA.

Application (FIuid-FIow Visualization)

Visual techniques for representing the time-dependent behavior of a computed 2-D flow around a cylinder are studied. The image was rendered on a Silicon Graphics 4D/220-GTX using in-house software.

Technique

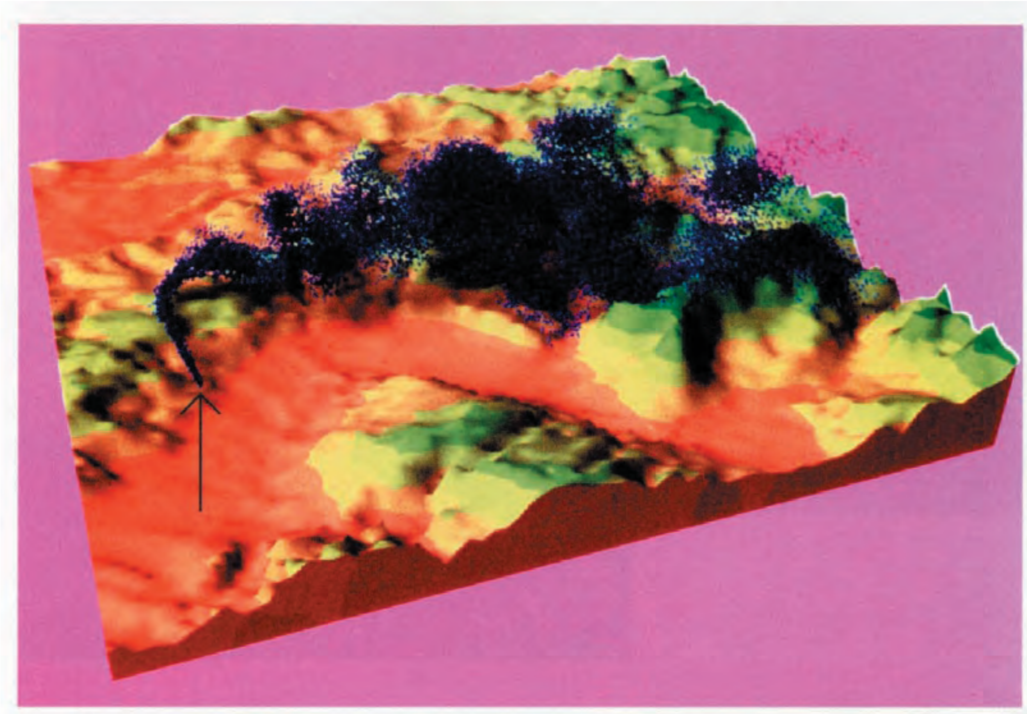
Topological visualization uses dynamical systems theory[1] to help understand 2-D fluid flow past a cylinder.[2] Time increases from top to bottom (back to front). Colored bands, lighting, and shading enhance the 3-D effect to help visualize fluid flow. The critical points in the flow (points at which the magnitude of the velocity is zero) are classified by type,[3] and those points are joined with tangent curves. Each surface is colored to depict its relation to a critical point. The light and dark candystriping provides cues to shape.

Hints

Understanding this technique requires some knowledge of dynamical systems theory; therefore, it should be used only with selected audiences. ~ Displaying vector fields as a set of tangent surfaces is much simpler and cleaner than presenting the fields as a set of arrows or curves. ~ **6-11** also demonstrates flow fields with dynamical systems theory.

[1] R. H. Abraham and C. D. Shaw, *Dynamics: Toe Geometry of Behavior,* Parts 1-4 (Santa Cruz, CA: Ariel Press, 1984).
[2] 5 Rogers and D. Kwak, "An Upwind Differencing Scheme for Time Accurate Incompress≠ible Navier-Stokes Equations," in Proceedings of the *AIAA 6th Applied Aerodynamics Confer≠ence,* American Institute of Aeronautics and Astronautics, Paper 88-2583 (June 1988), pp. 492-502.

[3]James L. Helman and Lambertus Hesselink, "Surface Representations of Two-



Shadows help locate a 3-D scalar field.

Melvin L Prueitt, Susan Bunker, and Tetsuji Yamada,

Los Alamos National Labora≠tory,

1 dependent variable

3 independent variables

Locates scalars

Meteorology

Application (Air Pollution)

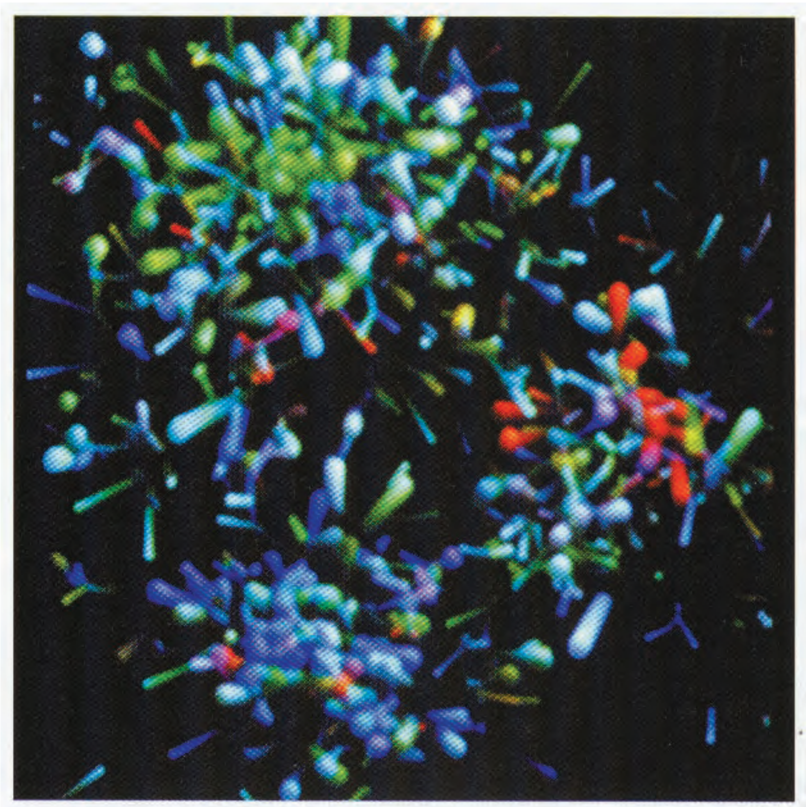
A computer simulation of air-pollution particulates from an oil shale plant in Colorado is studied. The in-house GRAFIC code running on a Cray supercomputer created the image, which was rendered on a Dicomed film recorder.

Technique

On a particle plot, the particulate density is represented by the number of blue dots per unit volume. The topography of the area surrounding the oil shale plant (indicated by an arrow on the image) becomes the reference plane below the dots. Surface height is keyed to color to redundantly encode height. Shadows from the dots are cast directly below to locate their *x-y* position on the reference plane. Perspective, shading, and the dark slice on the front edge, colored red to emphasize height, help create the 3-D effect.

Hints

Animating the particulates and rotating the viewpoint greatly improves under≠standing and the 3-D effect. ~ The technique of drawing shadows onto a reference plane can be used to locate other kinds of data; the topography could just as easily be a pipe, an experimental container, or an abstract surface. ~ This image also illustrates how shape can be used to show direction: the narrow base of the plume indicates the origin and the growing plume indicates the direction.



3 variables
Depicts interaction
Theoretical High-Energy Physics

Motion blur depicts 3-D interaction.

Jean-Francois Colonna, Lactamme (CNET, Ecole Polytechnique), France.

[1]Paul Haeberli and Kurt Akeley, "The Accumulation Buffer: Hardware Support for High Quality Rendering," Proceedings of SIGGRAPH '90, in *Computer Graphics* 24, 4 (August 1990).

Application (Strong Interaction Theory)

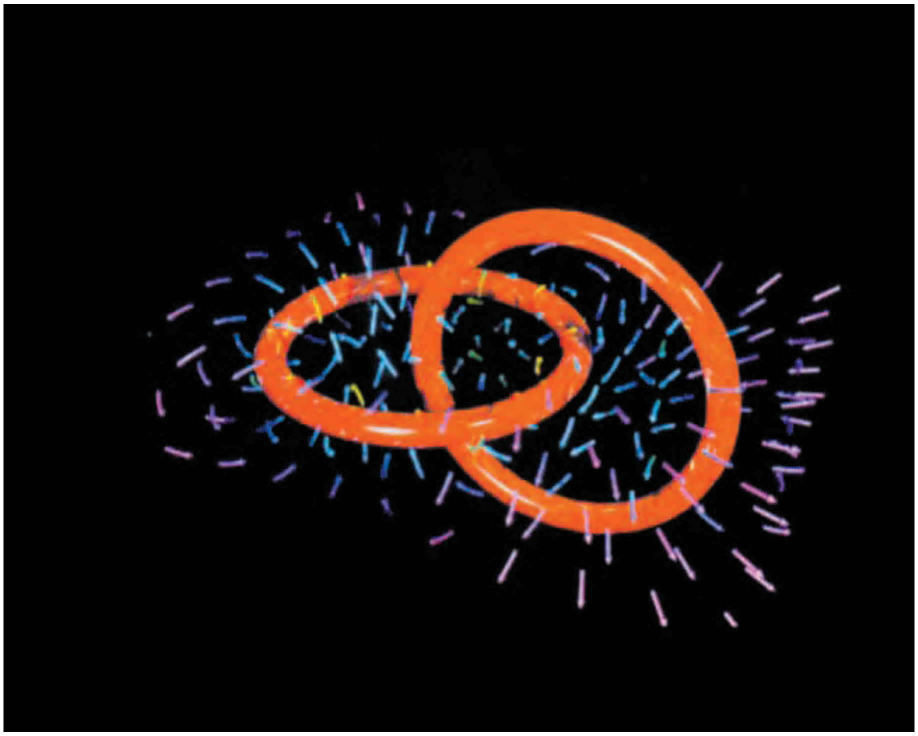
The computed interaction of gluons, quarks, and antiquarks is studied. The compu≠tation and the visualization were executed on a Silicon Graphics 4D 20 workstation with K, a machine-independent language.

Technique

In this 3-D model a simple shape (sphere) represents several types of particles. Sphere color identifies and differentiates each particle's properties. Sphere fuzziness, achieved by randomly displacing the surface points and then applying a low-pass filter, suggests the notion of probability. Cometlike tails created by a motion-blur technique' indicate velocity and suggest motion. Perspective and shading help create the illusion of depth.

Hints

Motion blur can be used to depict motion of any object. Here color and motion blur represent velocity of individual particles. ~ See **5-3, 5-6, 6-1, 6-6, 6-7, 6-9, 12-6,** and **12-10** for other ways to illustrate motion.



2 dependent variables
3 independent variables
Depicts vector field
Computational Physics

Color and regularly spaced, equal-length arrows depict a 3-D vector field.

Melvin L. Prueitt, Los Alamos National Laboratory, Los Alamos, NM, USA.

Application (Magnetic Fields)

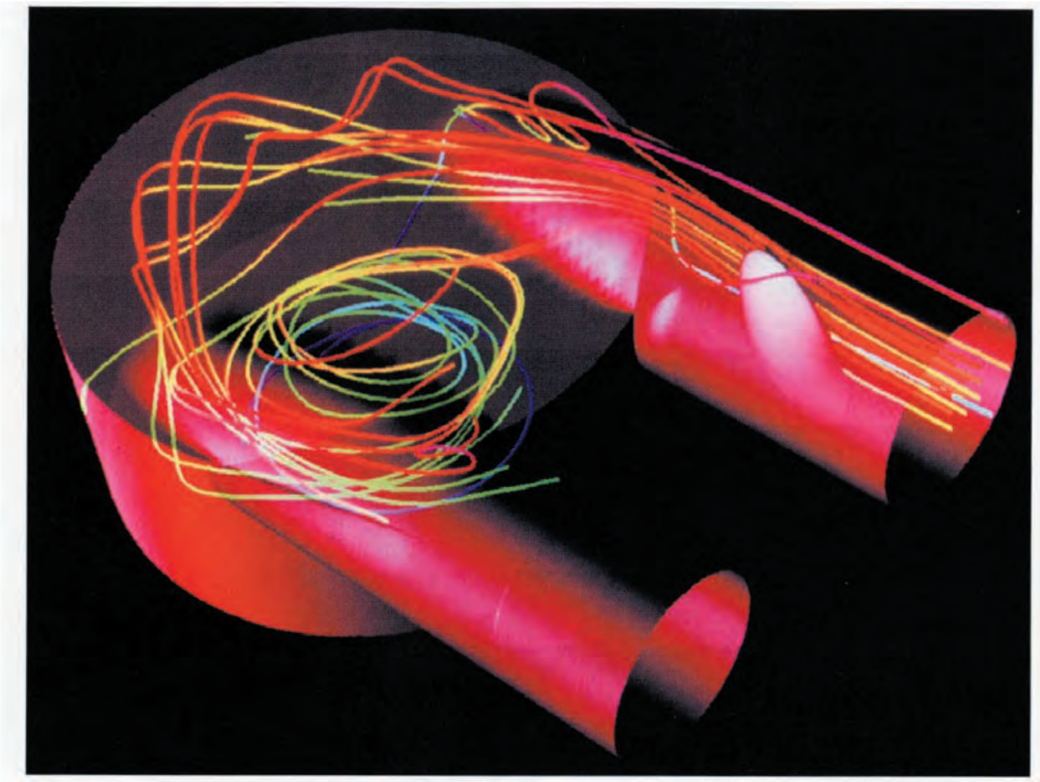
3-D magnetic fields around conductors are visualized. In-house software running on a Cray Y-MP supercomputer created the image, which was rendered on a Dicomed film recorder.

Technique ~

A 3-D vector plot shows the magnitude and direction of vectors at locations in a volume. Equal-length arrows, curved to follow the magnetic lines, represent the vector field. The arrows are colored magenta, blue, green-yellow, and red to indicate the magnitude of the variable (low to high) Arrows are computed on a lattice of equal width and length to enhance the 3-D effect when lighting and perspective are applied. The conducting rings that affect the magnetic field are texture-mapped and colored differently to differentiate them from the arrows.

Hints

The number of arrows may need to be adjusted; too many will clutter the image, too few will not show the field. ~ This technique can be used to model 3-D fields having orientation and magnitude~ ~ Excellent depth perception is possible with stereo pairs of slides and a stereo viewer.



3 dependent variables
4 independent variables
Locates path
Medicine

Color coding height to a particle trace helps locate its path.

Chris Gong, Cetin Kiris, Dochan Kwak, and Stuart Rogers, NASA Ames Research
Center, Moffett Field, CA,
USA.

[1] Cetin Kirit, Ph.D. Disserta-≠tion. Stanford University 1991/NASA Ames Highlights video 1990

Application (Biofluid Mechanics)

The behavior of the Penn State artificial heart is simulated. The vortex created by blood flowing through the central portion of the heart illustrates good wall washing over the entire chamber, reducing the chances that clots will form.[1] The computa≠tions were performed on a Cray Y-MP supercomputer and displayed on a Silicon Graphics IRIS workstation using NASA Ames PLOT3D, SURF, GAS, and Mrakevec.

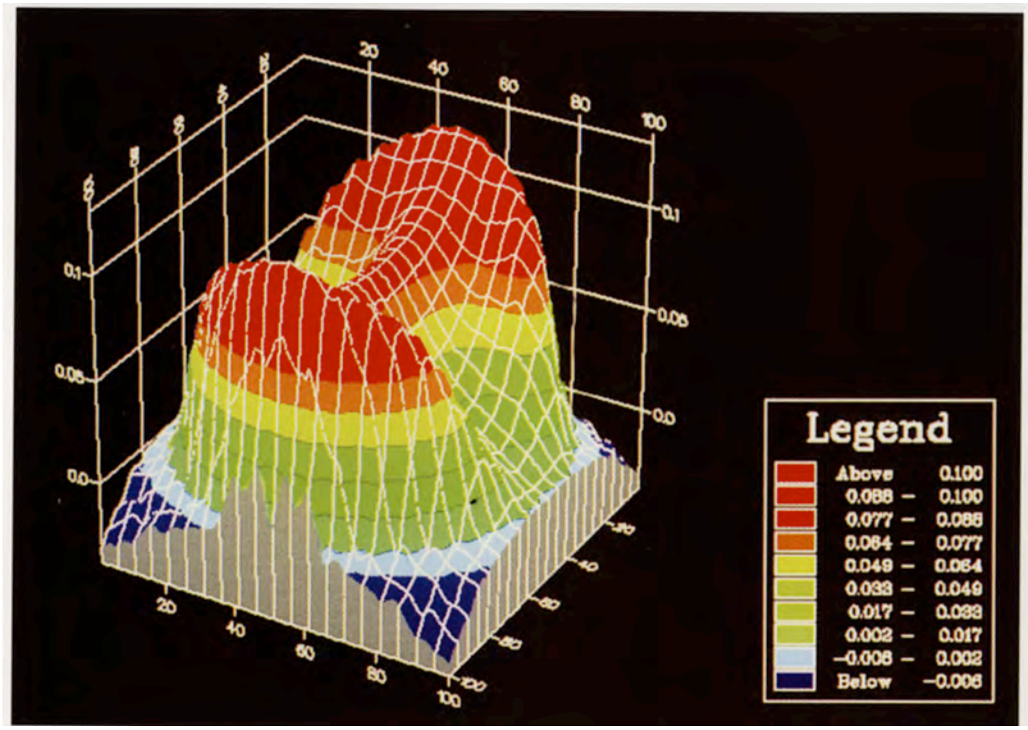
Technique

Particle traces simulating blood flow are computed over time and colored to indicate height (blue, low; red, high) within the artificial heart. Plotting the model 50% transparent reveals internal structure and the particle traces. Highlights emphasize the 3-D nature of the model.

Hints

The colored particle trace is useful to show path of flow and value of some variable along that path. ~ See **6-7** for a similar treatment of color paths.

7-2 **2-D Data**



1 dependent variable
2 independent variables
Locates structure
Mechanical Engineering

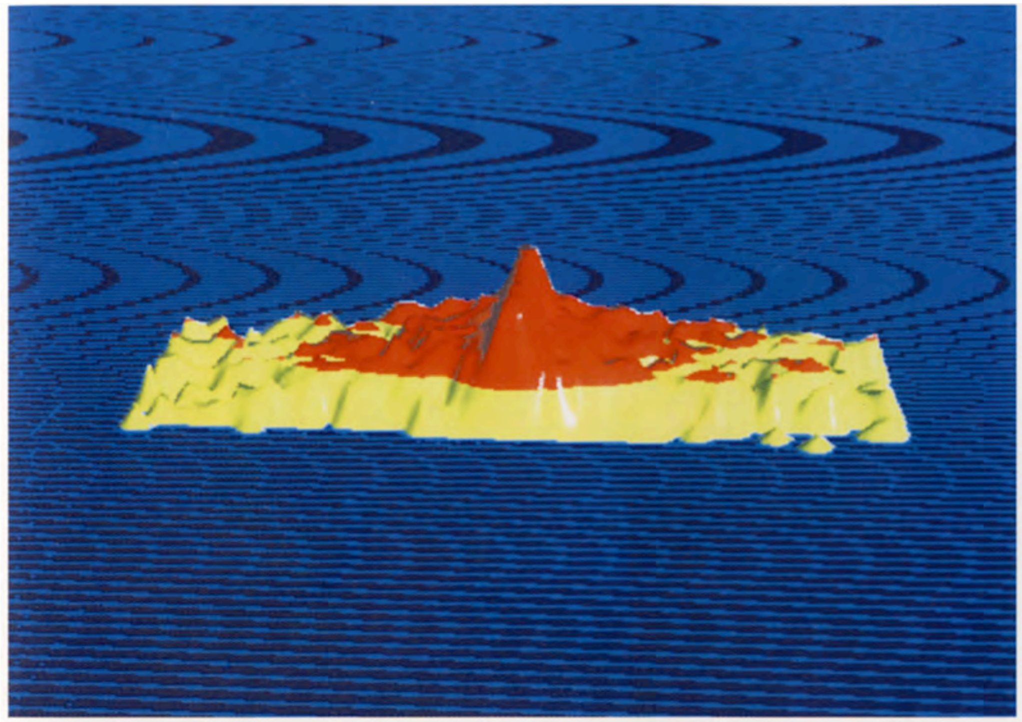
Grid lines locate value

Fred McClurg and Hoa D Nguyen,
Idaho National Engineering Laboratory
Idaho Falls ID

Heat transfer on a droplet in an electroconvective environment is simulated. the electric field interacts with surface charge giving rise to internal notion that results in a temperature distribution as plotted. This visualization was created on a DECstation 5810.

Technique
Grid lines for the base of the cube are overlaid on a pseudocolor surface plot and labeled to help locate coordinate values. Both height and surface color are used to determine temperature across a horizontal slice of the droplet. the vertical slices taken on tow axes and colored gray emphasize variation in temperature. The legend identifies the range of values for each color.

Hints
Orthogonal grid lines and scale numbers can be added to images to provide accurate locations for coordinates. The gray vertical surface could show the relationship between two variables while holding the third variable constant.



1 dependent variable
2 independent variables
Reveals structure
Computer Graphics

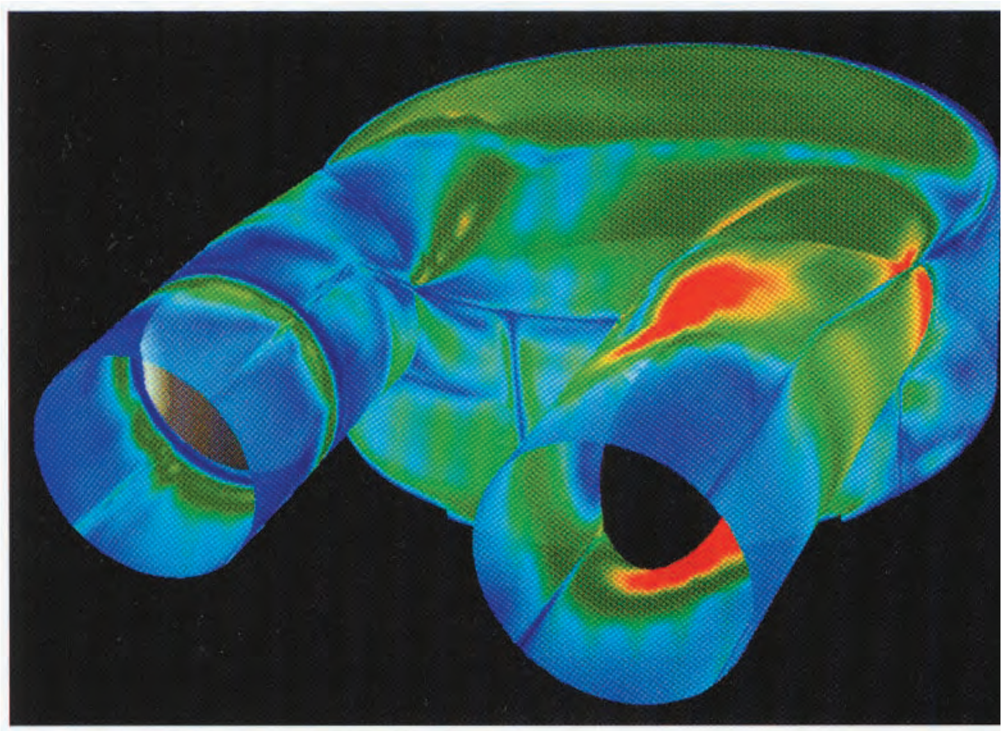
Mapping a critical value to a contrasting color reveals unexpected structure

Verlan Gabrielson, Sandia National Laboratories, Livermore CA

Application (Visualization)
Using the MESA package on a VAX 780 to study small 2-D filed reveals this unusual moiré-like pattern. Further study disclosed that the blue, patterned field that is supposed to be zero throughout is exactly zero in some places but only approximates zero in others. This accidental discovery led to the technique described here.

Technique
A pseudocolor plot helps validate a 2-D array of data. A critical value is assigned a color and the remaining values are mapped in contrasting colors. Height also corresponds to value. Any unexplained pattern or structure revealed by color or height indicates that further analysis is needed to determine if the unexplained pattern or structure is caused by errors in the data or in the rendering tools.

Hints
Assigning a contrasting color will quickly identify erroneous, widely varying data and is particularly useful in spotting deviations from the critical values, where minute differences can lead to incorrect answers. Whenever a rounding off error is suspected, this technique can be use to test or verify critical values.



Surface and Slice 8-1

1 dependent variable
3 independent variables
Locates regions
Medicine

Pseudocolored surface of a 3-D model quickly locates regions of high values

Chris Gong, Cetin Kiris, Dochan Kwak, and Stuart Rogers, NASA Ames Research Center, Moffett Field, CA,

Application (Biofluid Mechanics)

The Penn State artificial heart model is studied to locate regions of high vorticity so that the internal chamber can be appropriately designed. High vorticity implies high shear stress, which may result in damage to blood cells flowing near the solid boundaries. The computation was performed on a Cray Y-MP supercomputer and rendered on a Silicon Graphics IRIS workstation using NASA Ames PLOT3D; SURF; GAS; and Mrakevec.

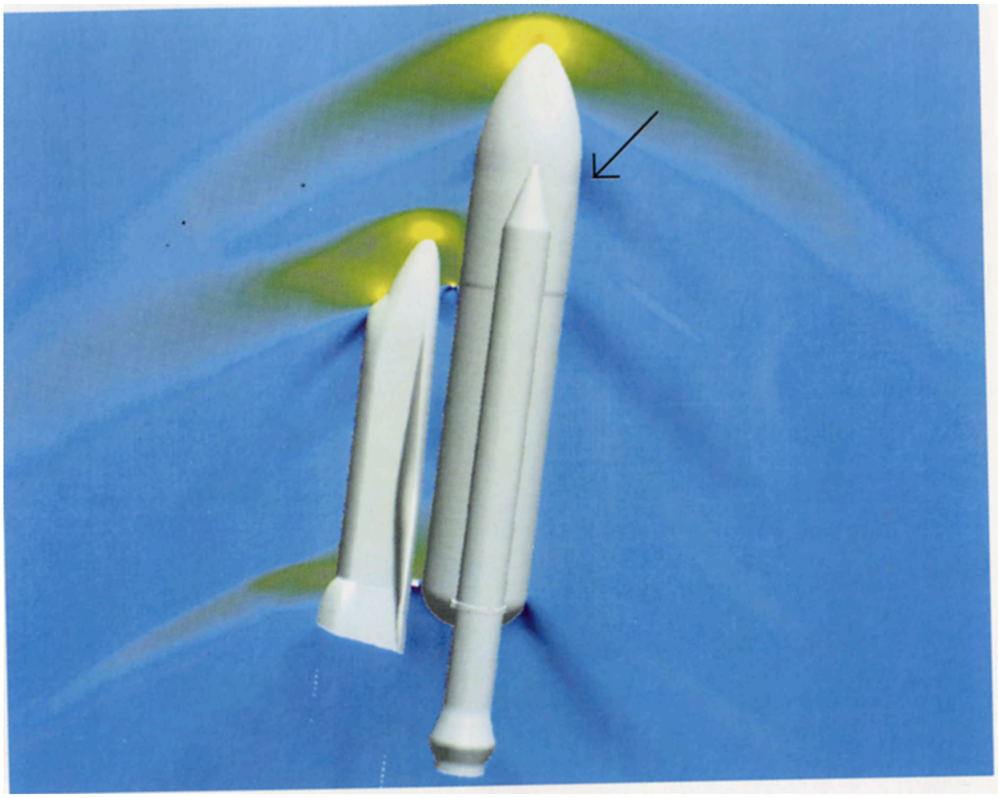
Technique

Pseudocoloring the model's interior surface locates maximum vorticity: blue, low; red, high. Making the model 50% transparent reveals internal mechanical structure to demonstrate how high vorticity is related to the physical features.

Hints

Making the model 50% transparent is a useful technique for relating internal structure to surface values. ~ Although 3-D vorticity data are throughout the volume, the image is simplified by representing only the data that touch a surface.

8-4 Surface and Slice



1 dependent variable
3 independent variables
Locates extremum
Computational Fluid Dynamics

Overlaying a 3-D model on a pseudocolor plot locates extremum

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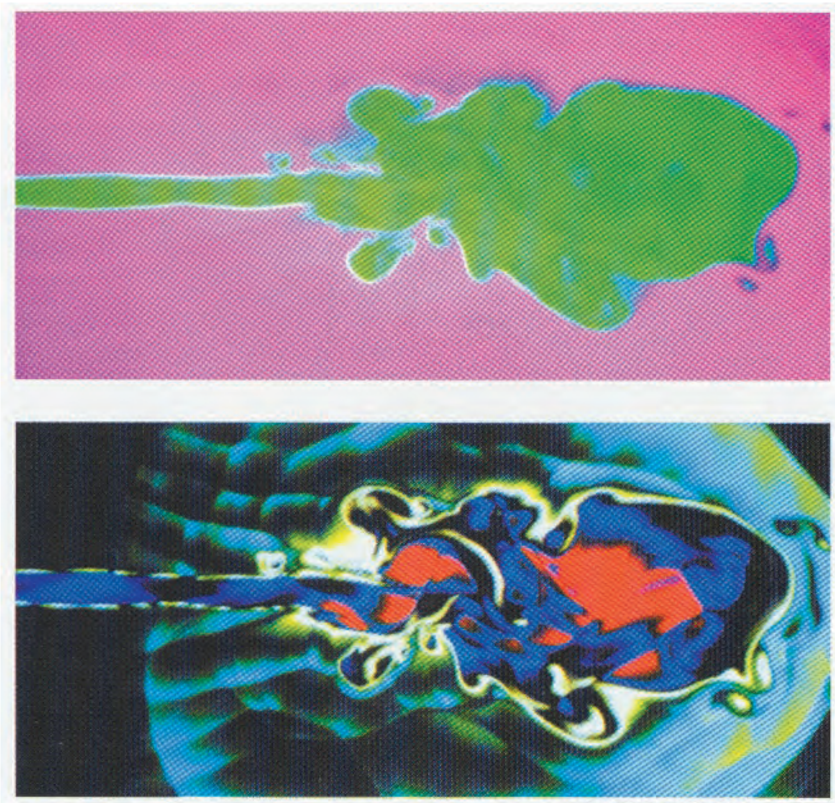
Application (Aerodynamics)
A calculation approximating steady flow around the NASA space shuttle in launch configuration after liftoff demonstrates that computational fluid dynamics can simulate some of the major shocks and expansions in the flow around a complex aerodynamic body. Pressure data were calculated on a Cray 2 supercomputer and rendered on a Silicon Graphics IRIS 320-VGX workstation using FAST.

Technique
The Marching Cubes algorithm generates a 2-D slice thought the 3-D pressure field. The color mapped to the pressure at each vertex is chosen according to the visible light spectrum (red, high; blue, low). The resultant slice is Gouraud shaded. The shuttle model is then combined with the slice to show the relationship between geometry and pressure. The shuttle's geometry is displayed as lighted, shaded surface to improve 3-D perception.

Hints
Several slices must be examined to understand all the important features in a 3-D field. At some angles or locations, slices may give misleading impressions. For example, the dark blue expansion near the top of the external tank (indicated by arrow) is caused not by the tank, but probably by the nose of the solid rocket booster, which is not intersected by the slice. Placing a model on a volume's slice provides a reference, but may be misleading for the uninitiated. The object may not be touching the slice at all, but is merely a reference. Combining a reference object with a volume slice must be done with care.

Multiform Visualization 11-1



A

1 dependent variable
2 independent variables
Reveals structure
Astronomy

B

Proper choice of color reveals structure.

Donna J. Cox, National Center for Supercomputing Applica≠tions**,** School of Art & Design, University of Illinois, Urbana, IL, USA; Michael Norman, National Center for Supercomputing Applications.

Application (Computational Astrophysics)

This simulation using a magnetohydrodynamics code shows the density of matter in an astrophysical jet in intergalactic space. Complex flow patterns and vortices are modeled. Images were rendered on a Silicon Graphics Workstation with data from an in-house application code on a Cray supercomputer.

Technique

Before-and-after pseudocolor maps constructed from the same data illustrate the dramatic change in meaning communicated by changing the color table. Changing the color that a data point receives reveals hidden structure in Figure B by creating color contrasts that the eye is better able to discern. 1

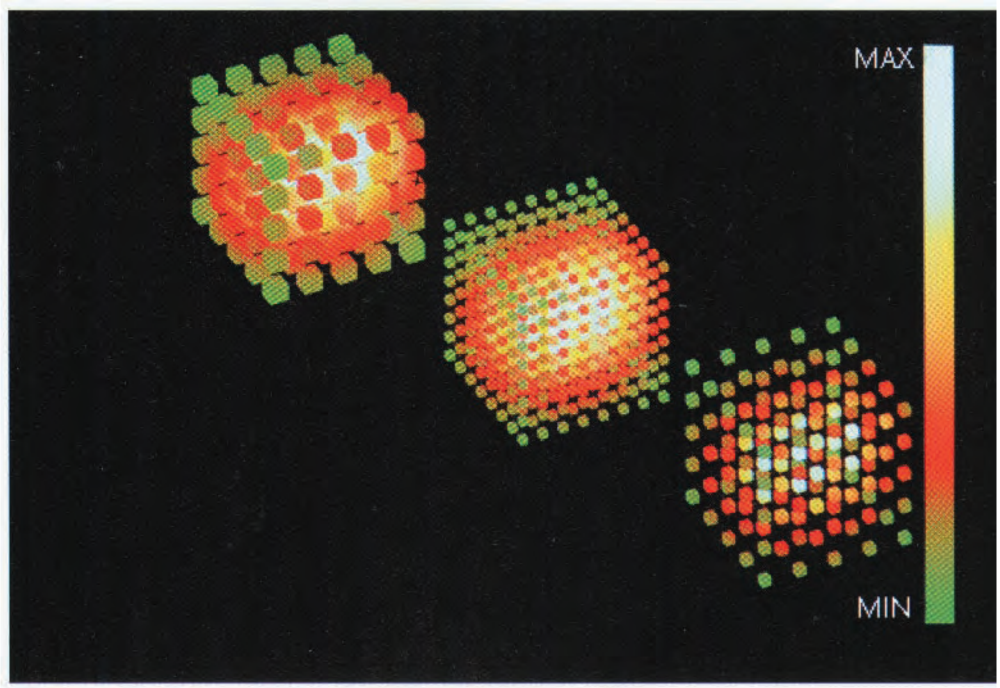
Hints

A color key as in Figure iv, page 4~, that illustrates the color table should be included if it is important to correlate color to the variable's value. ~ Another technique, histogram equalization, used in **11-3,** could automatically bring out detail. A more reliable way of discovering patterns, however, is to manually and interactively step through a collection of color tables.

[1] D. Cox, "Using the Supercomputer to Visualize Higher Dimensions: An Artist's Contribution to Scientific Visualization," Leonardo: Journal of *Art,* Science *and* Technology 21 (1988): 233-242.

[2] D. Cox, "The Art of Scientific Visualization," *Academic* Computing (March 1990): 20- 40; references at end of journal.

[3] G. Meyer and D. Greenberg, "Perceptual Color Spaces for Computer Graphics," Proceed≠ings of SIGGRAPH '80, in Computer Graphics (July 14-18, 1980).



1 dependent variable
3 independent variables
Reveals structure
Computer Graphics

Small cubes reveal 3-D structure.

Gregory M. Nielson, Arizona State University, Tempe, AZ, USA; Bernd Hamann, Missis≠sippi State University, Jackson, MS, USA.

Application (Visualization)

Invented data are used to demonstrate an interactive technique for visualizing volume. In-house software and the Silicon Graphics GL library rendered the image on the Silicon Graphics 4D 320 workstation.

Technique

Three cubic volumes illustrate three examples of the "tiny-cubes" technique for visualizing regularly spaced, coarse data throughout a cube.[1-3] The data value at each location determines the color of the vertices of the tiny cube drawn there. The tiny cubes are color coded according to the color key at right. A hidden-surface algorithm enhances the 3-D effect. Internal or external structure is best revealed by interactively adjusting three parameters of the code: number of cubes in each direction, size of cubes, and spacing between cubes.

Hints

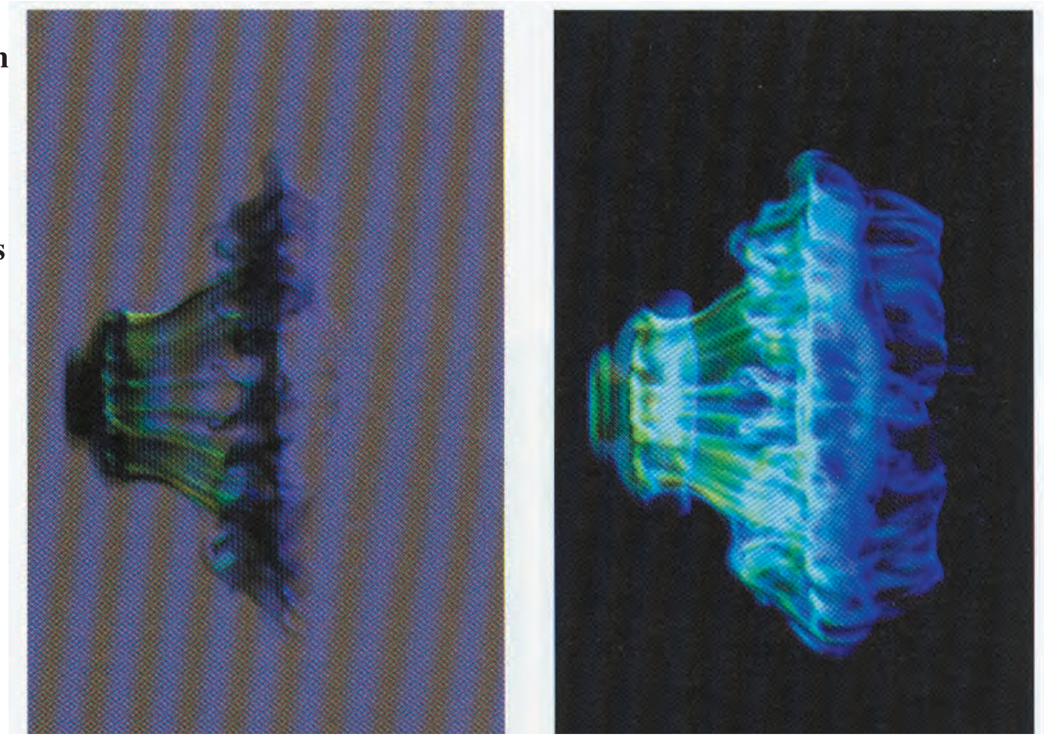
Rotating the cubic volume provides different views through the volume and significantly enhances understanding of the data. I To use this technique effec≠tively, one must keep the number of tiny cubes relatively small. It is difficult to see ''inside'' when the number of cubes in each direction is greater than twelve. Relatively large cubes tend to emphasize external features, but small cubes allow one to see internal structure. ~ See also **9-6,** which uses small spheres to reveal 3-D structure.

[1]Bernd Hamann, "Visualiza≠tion and Modeling Contours of Trivariate Functions," Ph.D. Thesis, Arizona State Univer-
≠sity, Tempe, AZ (1991).

[2] Gregory M. Nielson, Thomas A. Foley, Bernd Hamann, and David Lane, "Visualization and Modeling of Scattered Multivariate Data," *Computer* Graphics *and Applications* 11, 3 (May 1991): 47-55.

[3] Gregory M. Nielson and Bernd Hamann, "Techniques for the Interactive Visualiza≠tion of Volumetric Data," in *Visualization '90,* (Los Alamitos, CA: IEEE Computer Society Press, Octoher 1990), pp.45-50.

11-8
Multiform
Visualizatio



1 **dependent variable**
3 independent variables
Reveals structure
Computational Fluid Dynamics

Minute adjustments in opacity and background reveal structure.

Richard I. Klein, Michael J. Allison, and Thomas M. Kelleher, Lawrence Livermore National Laboratory, Livermore, CA, USA.

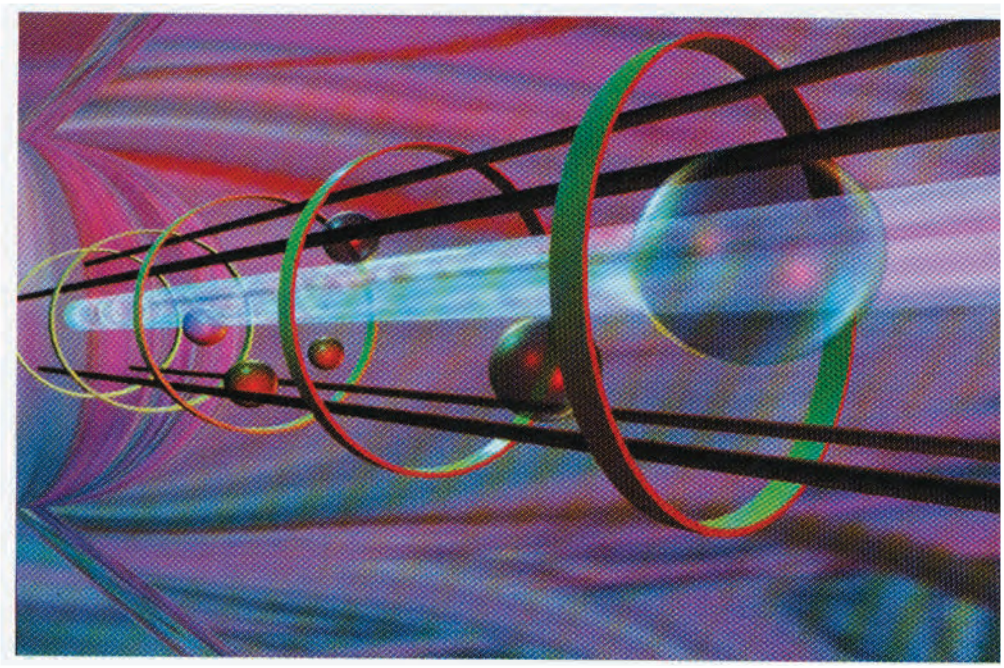
Application (Turbulent Fluid Flow)
The structure of fluid flow is studied by modeling the changes that occur when a spherical, interstellar cloud is subjected to a strong shock from a supernova explosion. The computational model was executed on a Cray Y-MP supercomputer and rendered on a Stardent computer with in-house software.

Technique
The computational model’s 3-D adaptive mesh is first converted to a rectilinear mesh and volume rendered with the compositing alpha-blend algorithm”[2] with the low-density and high-density values opaque. From the many images of the same data set rendered, two are shown here. Figure A shows the data with the very low-density fluid omitted so that structure occluded by that fluid can be observed. Figure B shows the very low-density fluid but uses a black background to enhance contrast to reveal complex, connected, very low-density structures.

Hints
Rotating the image, removing data, and changing opacities sometimes reveals more than one expects. Researchers originally thought the data had very little structure. Rotating the image, however, provided vantage points suggesting an intricate structure hidden by cloud material; that matter was then removed by selectively plotting data and adjusting opacity.

[1]Andrew Barlow, “New Workstation Graphics for Engineers,” *Computer-Aided Engineering* 9, 9 (September 1990): 40.

3-D Model Describes3-D Computer Art



Artistic depth cues achieve a 3-D impression.

Gregory MacNicol, Santa Cruz, CA, USA.

Application (Artistic Exploration)

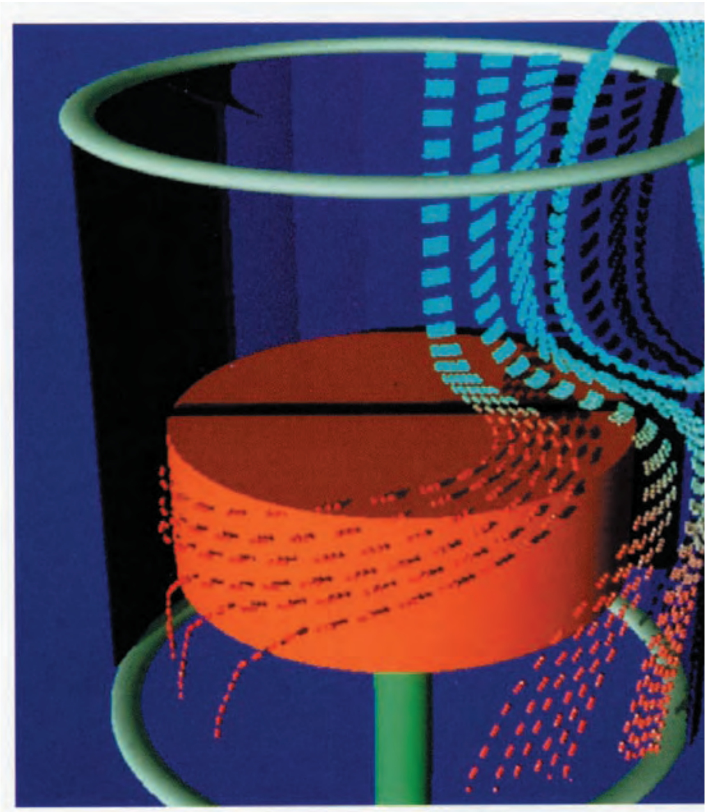
This imaginary scene was created to evaluate the rendering options and output quality of Crystal Graphics's Crystal 3D software running on a Micronics 486 with a Targa graphics board.

Technique

Perspective, opacity, color, and reflection are combined to give the 3-D effect. Objects converge and shrink, spheres become more opaque, and the color striations in the reflection narrow as they recede.

Hints

Unlike some techniques that require powerful computers, tools for creating and enhancing 3-D images such as this one are readily available on small desktop computers. ~ Artistically manipulated, desktop tools can create effective represen≠tations, such as the light beam in this image, which varies colors to suggest fluctuations in beam intensity~ (This same "beam" technique can be used to convey the motion of a high-velocity object, such as a comet or particle beams, or to convey electromagnetic radiation.) ~ By selecting eye-pleasing, coordinated colors that unify the image, the artist attracts viewer attention while improving comprehen≠sion and retention of information. Such unifying elements make any image more effective and help communicate.



2 dependent variables
3 independent variables
Correlates vector and scalar values
Computational Fluid Dynamics

Colored marker particles correlate vector and scalar values.

Verlan Gabrielson and Greg Evans, Sandia National Laboratory, Livermore, CA, USA.

[1]Greg Evans and Ralph Greif, "A Numerical Model of the Flow and Heat Transfer in a

Rotating Disk Chemical Vapor Deposition Reactor," Journal of *Heat* and Mass Transfer 109 (1987): 928-935.

2 Peter A. Watterberg, "MESA: A Ray Tracing Rendering Package, Programmers Manual," Sandia National Laboratories, Albuquerque,

NM, 1988.

Application (Chemical Vapor Deposition)

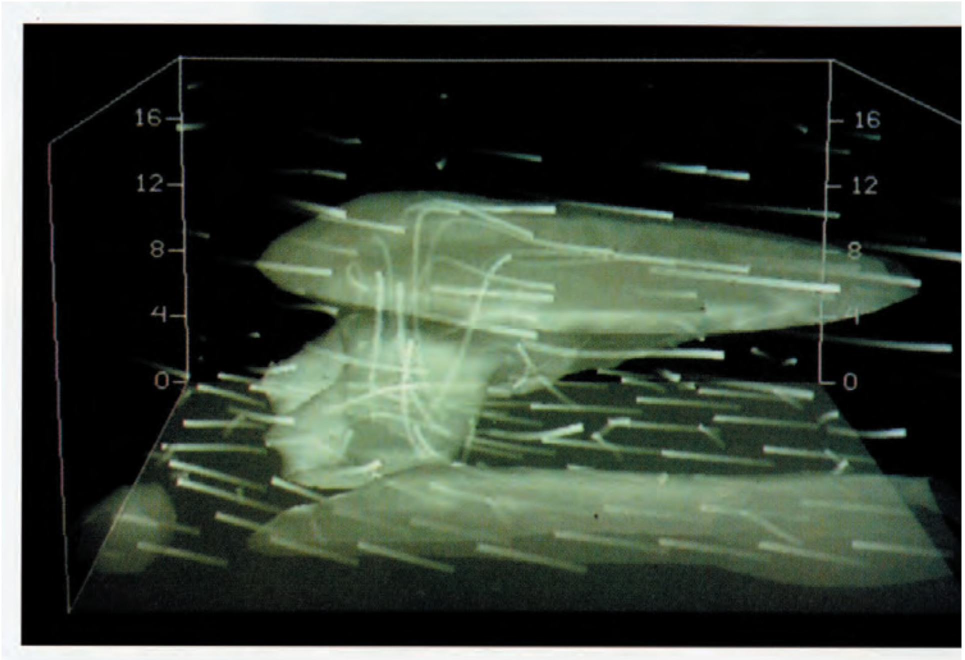
Data represent the flow-field solution of a Navier-Stokes equation in a cylindrical geometry. A simulation of flow and heat transfer in a rotating-disk chemical vapor deposition reactor[1] effectively reproduced laboratory experiments. The analysis was computed on a Cray supercomputer, and the visualization was computed on VAX 780 using the MESA package.[2]

Technique

Marker particles representing fluid particles are colored to show relative tempera≠ture (blue, cool; red, warm) and positioned to show relative speed. Relative speed is indicated by spacing the marker particles (close, slow; farther apart, fast). Two narrow tori describe the simulation boundary.

Hints

This image shows how effectively a collection of simple geometric shapes can communicate complex concepts. ~ Because the researcher knows the flow direction from experience, no directional cues are needed. ~ See **6-3** where color and motion blur show type of particle and relative velocity.



Motion 6-6

2 dependent variables

3 independent variables

Correlates isosurface and vector field

Meteorology

Motion-blurred trajectories are correlated to an isosurface.

William L. Hibbard and David A Santek, Space Science and Engineering Center, University of Wisconsin, Madison, WI, USA.

Atmospheric model written by Robert Schlesinger, University of Wisconsin Meteorology Department, Madison, WI, USA.

[2] W. Hibbard, “4-D Display of Meteorological Data,” (SIGGRAPH Proceedings, 1986 Workshop on Interactive 3D Graphics), Chapel Hill (1986): 23-36.

Application (Weather Simulation)

This atmospheric simulation of a thunderstorm was executed on a Cray X-MP supercomputer, and the image was rendered on an IBM 438~ using the in-house 4-D McIDAS software.

Technique

An isosurface of water vapor density and a vector plot are combined to permit their correlation.[2] Making the isosurface translucent permits viewing of part of the vector field that would otherwise be hidden. Cometlike objects representing the vector field show direction and speed. The length of the tail is proportional to speed. Motion blur adds to the sense of motion of the comets. The perspective edges of the bounding box convey a sense of 3-D, and a vertical scale helps estimate height.

Hints

Scaling for comet tail fade-out is a trial-and-error adjustment. ~ Motion blur can be used to study 3-D vector fields or to correlate scalar fields with vector fields. ~ Fog or cloudlike features are created and used in many ways; see **5-7, 5-9, 5-10, 9-2, 9-7, 10-4, 12-1,12-2, 12-7,** and **12-8.**