ACM SIGGRAPH
PRESENTS
A SPECIAL ISSUE OF THE ACM SIGGRAPH VIDEO REVIEW
ISSUE 44

VOLUME VISUALIZATION
STATE OF THE ART

Produced and Directed
by
Laurin Herr

Written by
Laurin Herr
Judson Rosebush

Additional Direction
Michael Maloy

Videography
Art Binkowski
Martin Brown

Video Editor
Jon Fordham

Assistant Video Editor
Donna Light

Text Editor
Trisha Gorman

Associate Producer
Natalie Van Osdol

Additional Camera
Bill Biagi
Brian Danitz
Elliot Einzig Porter

DuPont Logo Animation
Fantastic Animation Machine

Program Title Animation
Jan Hendricks

Desktop Publishing
Bobson Wong

Print Graphics
H. Buff Herr

VOLUME VISUALIZATION
STATE OF THE ART

ON-CAMERA SPEAKERS

Vincent Argiro, Ph.D.
Founder and Chairman
Vital Images, Inc.

Prof. Frederick P. Brooks, Jr.
Kenan Professor of Computer Science
University of North Carolina at Chapel Hill

Professor Thomas DeFanti
Director
Electronic Visualization Laboratory
University of Illinois - Chicago

Nick England
Director of Visualization Products
Sun Microsystems

Professor Henry Fuchs
Federico Gil Professor of Computer Science
University of North Carolina at Chapel Hill

Laurin Herr
President
Pacific Interface Inc.

Bill Hibbard
Researcher
Space Science and Engineering Center
University of Wisconsin at Madison

Xiaoping Hu, Ph.D.
Research Associate
University of Chicago

Mike Keeler
Director of Scientific Visualization
Ardent Computer Corp.

Marc Levoy, Ph.D.
Research Asst. Prof. of Comp. Science
University of North Carolina at Chapel Hill

Arthur Olson, Ph.D.
Director
Molecular Graphics Laboratory
Research Institute of Scripps Clinic

Professor Stephen M. Pizer
Professor of Computer Science
University of North Carolina at Chapel Hill

Professor Daniel J. Sandin
Co-Director, Electronic Visualization Lab
University of Illinois - Chicago

Alvy Ray Smith, Ph.D.
Co-Founder & Executive Vice President
Pixar

Ulf Tiede
IMDM
University Hospital Eppendorf - Hamburg

Craig Upson
Visualization Scientist
Stellar Computer

Turner Whitted
Technical Director
Numerical Design, Ltd.

James Winget, Ph.D.
Principal Scientist in Research & Development
Silicon Graphics

This program has been made possible through the generous support of the Electronic Imaging Division of E.I. du Pont de Nemours & Company.

The producers wish to thank
the organizers of the

Chapel Hill Workshop
on
Volume Visualization

Frederick P. Brooks, Jr., Workshop Chairman
Craig Upson, Program Committee Chairman

Also, for their most
gracious hospitality at U.N.C.
Henry Fuchs
Fay Ward
Mary Ducker
Linda Houseman

Special thanks to
Tom DeFanti
Dan Sandin
and
Maxine Brown
Electronic Visualization Laboratory
University of Illinois at Chicago

And very special thanks to
Rick Beach
Editor-in-Chief
ACM SIGGRAPH

Nick Gruin
Electronic Imaging Division
DuPont

TABLE OF CONTENTS

0:12:47 Xiaoping Hu on camera
0:13:26 *Voxel-Man:* Ulf Tiede, IMDM, University Hospital Eppendorf, Hamburg
0:13:52 *Living Cells:* Vincent Argiro, Vital Images, Inc.
0:14:09 Vincent Argiro on camera
0:14:25 *Lamprey Neuron:* Vincent Argiro, Vital Images, Inc.
0:14:38 *Neural Network:* Vincent Argiro, Vital Images, Inc.
0:14:46 Vincent Argiro on camera
0:14:57 *Translucent Heart:* Vincent Argiro, Vital Images, Inc.
0:15:05 *Cardiac Arteries:* Vincent Argiro, Vital Images, Inc.
0:15:07 *Beating Heart:* Shigeki Yokoi, Nagoya University
0:15:33 *Beating Heart in Chest:* Ulf Tiede, IMDM, University Hospital Eppendorf, Hamburg
0:15:51 Ulf Tiede on camera
0:16:42 *Inner View:* Karl Sims, Thinking Machines, Inc.

0:17:12 Why Now? What's the Benefit?

0:17:16 Laurin Herr on camera
0:17:27 *Point Clouds:* T. J. O'Donnell, EVL, University of Illinois at Chicago
0:17:46 *Bubble Man:* Norman Badler, University of Pennsylvania
0:17:51 *Metaball Man:* Koichi Omura, Osaka University & TOYO Links
0:17:57 *Fractal Landscape:* Richard Voss, IBM T.J. Watson Research Center
0:18:06 *Particle Dreams:* Karl Sims, Optomystic
0:18:23 Laurin Herr on camera
0:18:45 Fred Brooks on camera
0:19:22 *Study of a Severe Thunderstorm:* Robert Wilhelson, NCSA
0:19:33 Fred Brooks on camera
0:19:42 *Seismic Slides:* Paolo Sabella, Sun Microsystems, Inc.
0:19:59 *Seismic Animations:* Mosher & Johnson, Sun Microsystems, Inc.
0:20:16 Fred Brooks on camera
0:20:30 Dan Sandin on camera
0:21:09 *Send in the Clouds:* Geoffrey Gardner, Grumman Data Systems
0:21:17 Dan Sandin on camera
0:21:29 Alvy Ray Smith on camera
0:22:10 *Flame Puff Hypertexture:* Ken Perlin, New York University
0:22:12 *PPM Fluid Dynamics Simulation:* Porter & Woodward, University of Minnesota
0:22:15 *Quaternion Extension:* John Hart, EVL, University of Illinois at Chicago

0:22:21 Meteorology Applications

0:22:25 Laurin Herr on camera
0:22:52 *Weather Balloon illustrations*
0:22:57 *National Hail Research Experiment:* NCAR excerpts
0:23:09 *President's Day Storm:* Hibbard & Santek, SSEC, University of Wisconsin
0:23:28 Bill Hibbard on camera
0:24:00 *Visualization of Earth Science Data:* Hibbard & Santek, SSEC, U.of Wisconsin

0:24:20 Fluid Dynamics Applications

0:24:25 Laurin Herr on camera
0:24:33 *Fluid Dynamics Experiments:* NCSA
0:24:46 *PLJF Rendering:* van Cruyningen, Lorenzo & Hanson, Stanford University
0:25:56 *Exposing a Mixing Flow:* Kevin Wu, Sun Microsystems & Ray Snyder, Stanford U.
0:26:20 *Cosmic Jets:* Kamrath & Elvins, SDSC
0:26:45 *Turbulent Shear Flow:* Craig Upson, Stellar Computer
0:27:15 *PPM Fluid Dynamic Simulation:* Porter & Woodward, University of Minnesota

0:28:19 Engineering Applications
0:28:24 Laurin Herr on camera
0:28:31 *Turbine Blade:* Failure Analysis Associates
0:28:38 *Opaque Auto Cylinder Head:* Failure Analysis Associates
0:28:44 *Transparent Auto Cylinder Head:* Failure Analysis Associates & Pixar
0:28:54 *Ultrasonic Pipe Test:* Failure Analysis Associates & Pixar
0:29:00 *Helicopter Rotor Boot:* Failure Analysis Associates & Pixar
0:29:10 *Finite Element Material Stress Tests on Aluminum Cans:* Welling, Pittsburgh Supercomputer Center
0:29:18 *Damage Control Simulation:* John Winston, Rockwell International
0:29:27 James Winget on camera
0:29:45 *Volume Stress Analysis Examples:* James Winget, Silicon Graphics
0:30:16 James Winget on camera

0:30:30 Molecular Modeling Applications
0:30:34 Laurin Herr on camera
0:30:42 *Fluoropolymer Simulations:* P. Cabobianco, Cray & D. Dixon, DuPont
0:30:54 Frederick P. Brooks on camera
0:31:35 *Electron Density Map on Plexiglas:* Fred Richards, Yale University
0:31:42 *Richards' Box:* Fred Richards, Yale University
0:32:11 *Grip 75:* Computer Science Department, University of North Carolina at Chapel Hill
0:32:36 *Point Clouds:* T.J. O'Donnell, EVL, University of Illinois at Chicago
0:32:47 *AZT:* Fred Deck, EVL, University of Illinois at Chicago
0:33:05 *Tryptophan:* A. Olson, D. Goodsell, M. Pique, Research Institiute of Scripps Clinic
0:33:12 *DNA:* A. Olson, D. Goodsell, M. Pique, Research Institiute of Scripps Clinic
0:33:22 *SOD:* A. Olson, D. Goodsell, M. Pique, Research Institiute of Scripps Clinic
0:33:31 *Bovine SOD:* A. Olson, D. Goodsell, M. Pique, Research Institiute of Scripps Clinic
0:33:48 Arthur Olson on camera
0:34:02 *HIPIP:* A. Olson, D. Goodsell, M. Pique, Research Institiute of Scripps Clinic
0:34:26 Arthur Olson on camera

0:34:39 Mathematically-Defined Volumes
0:34:43 Laurin Herr on camera
0:34:50 *Hypertextures:* Ken Perlin, New York University
0:35:36 *Quaternion Extension of Julia Set:* John Hart, EVL, University of Illinois at Chicago

0:36:17 Volumes vs. Geometry
Voxels vs. Polygons
Some Questions About Terminology
0:36:19 Laurin Herr on camera
0:36:30 *Chart: Volume Data Set vs. Geometric Data Set*
0:36:36 *Chart: Isocontouring*
  Cervical Vertabrae Surface Rendering: Baker, SRI International
0:36:50 *Chart: 3-D Scan Conversion*
  Teapot: Arie Kaufman, Visualization Laboratory, SUNY at Stony Brook
0:37:06 *Chart: Surface Rendering vs. Volume Rendering*
0:37:32 Laurin Herr on camera
0:37:43 Alvy Ray Smith on camera
0:39:29 *Chart: Sampling Domain vs. Geometric Domain*
0:39:45 Laurin Herr on camera
0:39:56 *Chart: Volume Rendering Definition*

0:40:07	**Algorithmic Choices**
0:40:11	Laurin Herr on camera
0:40:20	*Regional Oxidant Models:* Whitted & Westover, Numerical Design, Ltd.
0:40:35	Turner Whitted on camera
0:40:50	*Chart: Volume Visualizaton Algorithmic Choices*
0:41:04	Alvy Ray Smith on camera
0:41:22	*Upper Chest:* Elliot Fishman, Johns Hopkins Hospital
0:41:43	Alvy Ray Smith on camera
0:42:46	Marc Levoy on camera
0:43:16	*Red Skull:* Marc Levoy, University of North Carolina at Chapel Hill
0:43:36	Marc Levoy on camera
0:44:17	Craig Upson on camera
0:45:06	Dan Sandin on camera
0:45:28	Laurin Herr on camera
0:45:43	Turner Whitted on camera
0:46:01	*Transluscent Head in Profile:* Lee Westover, Numerical Design, Ltd.
0:46:13	*Electron Density Cloud:* Lee Westover, Numerical Design, Ltd.
0:46:26	Turner Whitted on camera
0:46:38	Laurin Herr on camera
0:47:07	*SPLAT!*
0:47:12	**Visual Perception and Interactivity**
0:47:16	Laurin Herr on camera
0:47:28	Frederick P. Brooks on camera
0:48:00	Mike Keeler on camera
0:48:37	Henry Fuchs on camera
0:49:11	Marc Levoy on camera
0:49:44	*Dan's Dots:* Dan Sandin, EVL, University of Illinois at Chicago
0:49:57	**Hardware Issues**
0:50:00	Laurin Herr on camera
0:50:12	*Spinning Logo:* Silicon Graphics
0:50:18	*Rising Tracer Balls:* Stellar Computer
0:50:31	*Brain Visualization:* Richard Weinberg, USC and Ardent Computer
0:50:41	Henry Fuchs on camera
0:51:08	*Building:* Hewlett-Packard
0:51:15	*Auto:* Tektronix
0:51:18	*Piston*: Silicon Graphics
0:51:20	*Polygonal Chrysler:* Hewlett-Packard
0:51:41	*Evolution of Structure in the Universe:* Centrella, Drexel Univ. & Upson, Stellar
0:51:53	Henry Fuchs on camera
0:52:13	Turner Whitted on camera
0:53:32	Tom DeFanti on camera
0:54:36	*Send in the Clouds:* Geoffrey Gardner, Grumman Data Systems
0:55:17	**Future Visions**
0:55:20	Mike Keeler on camera
0:55:59	Frederick Brooks on camera
0:56:13	*Shuttle Air Flow:* Ardent Computer
0:56:19	*Blue Knee:* Vincent Argiro, Vital Images, Inc.
0:56:31	*Electron Density Visualization:* Mosher & Johnson, Sun Microsystems, Inc.
0:56:37	Frederick P. Brooks on camera
0:56:44	Alvy Ray Smith on camera
0:57:05	*Freddie*: Elliot Fishman, Johns Hopkins Hospital

0:57:14	*Downdraft Turbulence:* NASA Ames
0:57:28	Alvy Ray Smith on camera
0:57:36	Closing Montage
	Thunderstorm Simulation: Wilhelmson, NCSA
	Ray-Traced Golden Woman: H.-P. Meinzer
	White Face: Arie Kaufman, Visualization Lab, SUNY at Stony Brook
	Seismic Data Cube: Lee Westover, Numerical Design, Ltd.
	Purple Water Droplet in Benzene Tube: Mosher & Johnson, Sun Microsystems
	Blue AZT Molecule: Fred Deck, EVL, UIC
	Quaternion Extensions: John Hart, EVL, UIC
0:58:07	Laurin Herr on camera
0:58:24	Closing Credits
0:59:08	THE END

VOLUME VISUALIZATION

STATE OF THE ART

VIDEOTAPE TRANSCRIPT

INTRODUCTION

Laurin Herr on camera
Hello. I'm Laurin Herr.

This is a special issue of the SIGGRAPH Video Review devoted exclusively to volume visualization, one of the most exciting topics in the field of computer graphics today.

Images from The Chapel Hill Workshop on Volume Visualization

The Chapel Hill Workshop on Volume Visualization in May 1989 was the first major technical meeting to concentrate on this topic. Like other attendees, we were inspired by the enthusiasm of the organizers.

Opening Montage
Red Skull: Levoy, UNC at Chapel Hill
Electron Density Cloud: Westover, Numerical Design, Ltd.
Voxel-man: Tiede, University Hospital Eppendorf, Hamburg
American Clouds: Hibbard & Santek, SSEC, U. of Wisconsin
Three-Toed Sloth: Mosher & Johnson, Sun Mircosystems, Inc.

We've managed to collect many of the best volume images shown at the workshop, plus many more from developers and users across America, Germany and Japan.

As our research progressed, we visited university labs for additional insight. And we interviewed expert after expert after expert. Twenty in all.

Earthquake Simulation: Thinking Machines

In the next sixty minutes, we're going to answer some key questions.

What is volume visualization?

Why is it coming into prominence now?

How is it used and what are its benefits?

What are the basic algorithms and how do they work?

What are the key technical tradeoffs?

And what are the future issues?

Laurin Herr on camera
Volume visualization is a new general purpose concept. It is elegant, clean, versatile and powerful. It works well for many applications and can handle both scanned and computed data as input.

Volume visualization brings computer graphics and image processing together in the sense that it borrows from both and transcends both.

Volume visualization liberates computer graphics from the constraints of polygonal geometry, and, as a result, it is stimulating a lot of new ideas. And these, in turn, should help the field evolve rapidly, especially in terms of software.

But software alone will not be enough. Volume visualization puts new demands on hardware systems for more compute power, more memory, faster communications and new types of displays.

WHAT IS VOLUME VISUALIZATION?

Laurin Herr on camera
Experts in this field emphasize that volume visualization is *not* traditional computer graphics. Traditional computer graphics defines 3-D objects primarily by using polygons -- 2-D closed surfaces residing in 3-D space.

Chalice sequence: James Blinn, JPL

In this classic progression by Jim Blinn, you can see the individual polygons quite clearly in wire frame and hidden line representations. Smooth shading seems to make the individual polygons disappear. Adding texture increases the realism. But, throughout, the fundamental building block is still the polygon, still the geometrically defined surface.

Tin Toy: Pixar

Here's an example of how good traditional computer graphics has gotten after decades of R&D: the Academy Award winning *Tin Toy*.

Laurin Herr on camera
So what is volume visualization?

We have to start with the underlying data representation.

Cube's Transformation: Ron Resch, Evans & Sutherland

In volume visualization, data is commonly represented as a 3-D volume-filling lattice of individual volume elements called voxels. Each voxel is a quantum unit of volume, a discrete value at a discrete address in XYZ space, the 3-D equivalent of a 2-D pixel.

Here, individual cubes are analogous to a single voxel, and the total aggregate of voxels defines a volume data set.

Tom DeFanti on camera
Traditional computer graphics has relied very heavily on the concept of the polygon as being the unit that helps describe the surface. The nice part about polygons is you can use mathematical entities simply to scale them, so you can make them any size you want and then render the polygons and use various tricks to make the edges look smooth and so on. It's very well understood now and you can buy hardware that

does it very quickly, so you can get real-time polygonal surfaces of a hundred thousand polygons per second.

The volume visualization, on the other hand, does not rely on a polygonal based approach; it relies primarily either on raw data in this n-by-n-by-n lattice; or perhaps, if you extend the concept a little bit, you get to mathematical functions that give you not polygons as results, but values in this n-by-n-by-n lattice that are then used to create the image.

Craig Upson on camera
Well, volume visualization differs from traditional 3-D computer graphics in that it uses new primitives. It uses volumetric primitives, primitives that go beyond the traditional primitives that we know about, you know -- zero-dimensional primitives are points, one-dimensional primitives which are lines or curves, two-dimensional primitives which are surfaces or images themselves, and volumetric primitives are three-dimensional primitives -- hypersolids -- I mean, hyperpatches which we use to compose complete volumes of data.

Thunderstorm Simulation: Craig Upson, Stellar
Inner View: Karl Sims, Thinking Machines Corporation
Cosmic Jets: Anke Kamrath and Todd Elvins, SDSC

Consequently, when you don't decompose a complete volumetric data set into lower dimensional primitives, like zero- to two-dimensional primitives, you use all the data that's in the data set. This results in images that tend to have really fuzzy aspects to them, cloudlike phenomena; and in general, they have structures that aren't at all the same as what you would see in a traditional image that was generated by normal computer graphics.

Marc Levoy on camera
Volume visualization starts from a set of sample points distributed through three-dimensional space, whereas traditional computer graphics starts from a set of geometrically defined primitives, such as polygons. And so the kind of mathematics that you need to deal with them is different.

Chart: Volume Math vs. Geometric Math

Volume visualization uses all the literature and the theory of image processing, of sampling theory, of Fourier analysis, whereas traditional geometric computer graphics uses 4-by-4 homogeneous transformation matrix and scan conversion and mathematical description of curves and surfaces, and a lot of that kind of math.

Tom DeFanti on camera
The difference between volume visualization and surface rendering is akin to the difference between raster graphics and vector graphics.

Brain Peel: Hans-Peter Meinzer, German Cancer Research Institute, Heidelberg

There's going to be a whole bunch of algorithms, which we can't even think of right now, that are going to develop using this fundamentally clean way of storing data.

MEDICAL APPLICATIONS

Laurin Herr on camera
Doctors have always wanted to look *inside* their patients to see what's really going on. There's more here than meets the eye.

Ocular Tumor Treatment Simulation: Wayne Lytle, Cornell University, CNSF

Much of the pioneering work in volume visualization has emerged in medicine because of the profusion of high quality medical scanners which produce voxel data sets.

Here we see how the shape of an ocular tumor and the torn retina it has produced can be extracted from the cube of data created by an ultrasound scanner. Each slice grabbed by the scanner is manually traced and a polygonal surface generated.

Rotation shows the 3-D relationships of the tumor, the retina and the other parts of the eye.

Mouse Embryo: Eihachiro Nakamae, Hiroshima University

In this example, actual cross-sections of physical tissue were examined under a microscope.

Again, tissue boundary information was extracted through manual tracing, and polygonal surfaces were generated. Variable transparency and color were used to visualize the many different tissue types found in this mouse fetus.

Such techniques have several drawbacks. Manual tracing is tedious. Once the surface information has been extracted, the remaining contents of each slice are ignored. And the many semitransparent layers are hard to read.

Visualization of the Brain: Arthur Toga, UCLA

Here, computerized thresholding techniques are used to automatically extract the edges of the brain, allowing faster creation of a surface model.

In this case, the original slice contents are not discarded, allowing the researcher to examine various internal cross-sections while the surface representation provides helpful reference to the external appearance of the brain.

Once again, transparent surfaces and rotation are used to reveal the 3-D relationships of various structures.

Stephen Pizer on camera
The difficulty with the surface visualizations is the need to make that intermediate representation of the surface.

Radiation Therapy Simulation: Sherouse, N. Carolina Memorial Hospital Chapel Hill

That's painful for the treatment planner, but it's absolutely impossible for the diagnostician because he's in the business of exploring a three-dimensional patient and understanding what it is that the data shows. If he has to first understand it in 3-D to present it in 3-D, he might just as well not have the final presentation.

Mr. Yorick's Skull: Goldwasser & Liebman, University of Pennsylvania

Direct representation of the voxels does away with the need to define any intermediate surface. This 1984 animation, one of the first to be generated directly from CAT scan data, was recorded in real time at the University of Pennsylvania's GRASP Lab.

Hips: Pixar and Elliot K. Fishman, Johns Hopkins Hospital

Then, in 1986, Pixar stunned us with this dramatic color sequence, produced in collaboration with Dr. Elliot Fishman at the Johns Hopkins Hospital. One of Pixar's key innovations was a percentage classification model to replace the binary thresholding technique typically used in the past to classify voxel data.

Density Chart: Elliot Fishman, Johns Hopkins Hospital

Notice how thresholding is an all-or-nothing approach, while the percentage model provides a smoother boundary transition.

This shows a typical classification of CAT scan density values into muscle, bone and fat using the percentage model.

Rotating Skull: Elliot Fishman, Johns Hopkins Hospital

Dr. Fishman and his colleagues have successfully applied this new visualization capability to various aspects of medical research, surgical planning and diagnosis.

Lung: Elliot Fishman, Johns Hopkins Hospital

This representation of a lung is one of their newest images.

Bronchial tubes: Elliot Fishman, Johns Hopkins Hospital

By fine-tuning their data classification parameters, they are able to reveal deeper structures, like the bronchial tubes, seen here in such detail.

Nick England on camera
Data classification is probably the hardest thing that we've got to do. And it's one of the places where we haven't made much progress yet, I think. Most of the people who are in my end of the business, that is, vendors providing hardware and software, are starting out with the simple classification techniques, right?

Brain: Chuck Mosher and Ruth Johnson, Sun Microsystems, Inc.

We can say, "Well, if it's in this density range, then it's probably bone. If it's in this density range, then it's probably skin. Or maybe it's probably brain. Or maybe it's probably something else." Those simple classification techniques break down in the field in real use.

Nick England on camera
And so we're going to see a lot more development activity, I think, in things that are similar to what goes on in image analysis or image recognition -- image understanding systems. We're trying to develop some understanding of regions and use some automatic tools to help us do that, although it's going to be difficult. It's going to be very difficult.

Integrated 3-D Display of MRI & CT Images of the Brain: Xioaping Hu, University of Chicago Hospitals

Laurin Herr off camera
Researchers at the University of Chicago are also trying to improve their understanding of regions in a volume. This is crucial to building a neurosurgical simulator that can correlate surface anatomy with the location of deep-seated tumors or functional anomalies.

To do this, they have developed methods to register the volume visualizations generated from CAT, MRI and PET scanners, each of which reveals only part of the puzzle due to inherent differences in the scanner technology itself.

Xiaoping Hu on camera

We originally tried to use surface rendering -- surface models -- of the brain and it didn't work so well. So we switched to volume rendering, which proved to be essential in the producing of the specific anatomy of the brain surface. The problem that we actually have is segmentation. You cannot do segmentation of medical images completely automatically, because there are a lot of artifacts involved in these medical images.

Voxel-Man: Ulf Tiede, University Hospital Eppendorf, Hamburg

Laurin Herr off camera

Despite the very real problems of artifacts and data classification, volume visualization offers doctors such a powerful new tool that research hospitals around the world are developing systems along the same lines. For example, University of Hamburg researchers have concentrated on integrating not only the various types of volume data, but also different shading techniques and an assortment of user interface tools, like cutting planes.

Living cells: Vincent Argiro, Vital Images, Inc.

The volume visualization techniques we've seen applied to neurosurgery are now being adapted to neurobiology, allowing brain structures to be visualized at the cellular level using data from laser confocal microscopes, a new type of scanner with sub-micron resolution.

Vincent Argiro on camera

What we're really trying to understand is how the brain develops at the microscopic level. The brain is a three-dimensional structure. You can't understand its circuitry in 2-D the way you can understand chips in 2-D, because the brain is wired in 3-D.

Lamprey Neuron: Vincent Argiro, Vital Images, Inc.

To understand the connectivity, to understand the way the pathways develop, you need to understand the thing as a volume, as a developing volume in time, and at submicron resolution with enormous complexity.

Neural Network: Vincent Argiro, Vital Images, Inc.

And so the laser microscope provides the opportunity to generate directly very high resolution data describing the inherent geometry.

Vincent Argiro on camera
You're developing things in a volume form, and we felt that it was most directive to render it directly as a volume rather than to try to use geometric methods.

Translucent Heart: Vincent Argiro, Vital Images, Inc.

Laurin Herr off camera
In the area of cardiology, volume visualization can be used to study the structure of the heart,

Cardiac Arteries: Vincent Argiro, Vital Images, Inc.

or just the structure of its blood supply network.

Beating Heart: Shigeki Yokoi, Nagoya University, Japan

A beating heart, though, holds some special visualization challenges. The scanner must be synchronized to the heart's natural rhythm and multiple exposures made at every step in the pumping cycle to eventually produce an "average" motion sequence.

Researchers at the University of Nagoya in Japan were particularly interested in the blood-filled volumes within the heart, displayed here using simple, but fast, Z-buffer depth cueing to show three dimensionality.

Beating Heart in Chest: Ulf Tiede, University Hospital Eppendorf

In this visualization, the data set contained 28 MRI slices for each of 12 heart phases, so University of Hamburg researchers used a transparent grey level shading to create a kind of "visual averaging" that seems to communicate a fuller sense of the heart's structure in motion.

Ulf Tiede on camera
Volume data structure has the advantage that we can produce 3-D images and that these images are especially of very high information for the non-radiologist. This is very important. The radiologist can always do his job on two-dimensional slices. This is what he has learned during several years, but especially the non-radiologist cannot do mental 3-D reconstruction from 2-D slices. And so it is essential to give other people in the hospital the possibility to have a look at these image volumes in the form of three-dimensional images.

Inner View: Karl Sims, Thinking Machines Corporation

WHY NOW? WHAT'S THE BENEFIT?

Laurin Herr on camera
Over the years, the limitations of polygon-based 3-D geometric models has led a number of computer graphics researchers to develop alternative techniques to represent volumes.

Point Clouds: T. J. O'Donnell, EVL, University of Illinois at Chicago

One of the oldest is point clouds, which imply a volume without explicitly defining a surface. This permits "see-through" viewing without transparency. In terms of data structure, point clouds are a classical 3-D point list, well-suited to fast display on the hardware of the early '70's.

Bubble Man: Norman Badler, University of Pennsylvania

Then there is solid modeling using parametric shapes -- in this case, spheres --

Metaball Man: Koichi Omura, Osaka University & TOYO Links

or, in this case, easily deformed spherical primitives called metaballs.

Fractal Landscapes: Richard Voss, IBM T.J. Watson Research Center

[Here we see] fractals, which mathematically generate polygonal shapes of great naturalistic complexity without a detailed geometric data base,

Particle Dreams: Karl Sims, Optomystic

and particle systems, whereby objects are modeled as a cloud of particle primitives that define its volume, but not its exact shape and form. The particles themselves can change over time, making it feasible to represent dynamics impossible with traditional polygonal models.

Laurin Herr on camera
Voxel-based models attracted the attention of researchers starting in the '70s, but were largely abandoned as being too slow and too expensive at the time. Memory requirements were particularly onerous. And immediate application potential appeared limited.

Why, then, is volume visualization experiencing such an explosion of activity just now?

Fred Brooks on camera
The reason why volume visualization has become a timely intellectual interest is twofold. One is, until this past generation of supercomputers, computational scientists could not solve three-dimensional models. They could solve only two-dimensional slices of models. So, for even simple models such as the weather above the North American continent, twenty-five years ago people would compute three layers of weather, and then five layers and then seven layers,

Study of a Severe Thunderstorm: Robert Wilhelson, NCSA

and now we begin to deal with many layers. Instead of just visualizing it as three sheets, one has to visualize it as a volume of results that the computational model has produced.

Fred Brooks on camera
The other thing is that the instrumentation methods available for determining how creation works [are] now able to take three-dimensional measurements.

Seismic Slides: Paolo Sabella, Sun Microsystems, Inc.

Seismic Animations: Mosher & Johnson, Sun Microsystems, Inc.

So seismic data will yield a lot of what's under the surface of the earth that is in fact three-dimensional data. And, of course, there were primitive instruments for measuring geological rock formations or whatnot twenty-five years ago, but as we've come up to the present these have become so much more sophisticated that the mass of measured data in three dimensions has gone way up. There's a third reason, and that is that the computational and graphical technology can realistically tackle this problem now and could not a decade ago.

Fred Brooks on camera
So there are two kinds of new needs: computational models of reality and instrument data from reality. Plus a new capability, in terms of computational power for the graphics.

Dan Sandin on camera
One of the things that's made volume visualization so popular right now is that finally we have equipment that can hold that much memory. I mean, 512-by-512 is a big number -- it's a quarter of a million. You multiply that by 512 again and you end up with lots of millions. And we finally have equipment that can hold that much

memory. And so the potential for exploring new algorithms -- new methods -- of doing visualization is very rich and everybody in computer graphics that looks at it feels like, "Oh, it's a beginner's mind. There's a whole new world here and there's a million directions to go."

Send in the Clouds: Geoffrey Gardner, Grumman Data Systems

One of the nice things about volume visualization is it can represent continuous things in a continuous way. For instance, it can represent a surface as an amount of reflection proportional to how fast the characteristic is changing. Rather than having it in a binary way to say, "Here is the surface,"

Dan Sandin on camera
it can say, "There's more surface here when the rate of change is higher" and represent that as a partially reflecting surface. So you can keep going through and accumulating things that are behind it.

Alvy Ray Smith on camera
Something that volume visualization adds to the universe is it increases our repertoire of models, of scenes that can be viewed. I and my colleagues have always claimed that the richest source of imagery was the real world. And we've captured it over the years in the forms of digitized photographs that are either used as backgrounds or as texture maps onto the surfaces of synthetic objects. Okay. What we've done now, of course, is just add three-dimensional data sets instead of 2-D data sets -- as well as 2-D data sets, to -- as candidates for being included in our scenes:

Flame Puff Hypertexture: Ken Perlin, New York University

puffs of smoke, for example,

PPM Fluid Dynamics Simulations: Porter & Woodward, University of Minnesota

or chaotic turbulent flows,

Quaternion Extension: John Hart, EVL ,University of Illinois at Chicago

or voluminous things that are difficult to represent geometrically.

METEOROLOGY APPLICATIONS

Laurin Herr on camera
One of the greatest things about volume visualization is its general purposeness.

In the medical and seismology examples we've shown, the visualization goal has been to look inside something that is not normally viewable.

In meteorology, though, the problem is somewhat different. After all, anybody can look up at the sky and *see* the weather.

In meteorology, the visualization goal is to somehow comprehend the inner workings of dynamic events that have enormous scale and complexity.

Weather Balloon Illustrations

National Hail Research Experiment: NCAR

Meteorologists have been collecting weather information for centuries. In modern times, this effort has been systematized and extended to include weather balloons, weather satellites, various forms of radar, and of course, reports from airplanes, ships and ground stations.

President's Day Storm: Hibbard & Santek, SSEC, Univ. of Wisconsin

Severe storms have been of particular concern because of their destructive power. A key technique in understanding the behavior of storms is their simulation using supercomputers. And much of this research involves modeling the atmosphere as a n-by-n-by-n lattice. Volume visualization is a natural fit.

Bill Hibbard on camera
We need to look at the atmosphere in three dimensions with volume visualization techniques because the atmosphere is a volume, because you just look out the window and you can see it's a three-dimensional volume. It has extents in all three dimensions. And it's time-varying. And it's multivariant. That is, there are many interacting physical parameters in that volume. And so we need to see the atmosphere in all of those ways. We need to see it as a volume. We need to see it evolving over time in that volume. And we need to see the multiple parameters interacting in that volume in order to understand what's really going on.

Real-Time Interactive Visualization of Earth Science Data: Hibbard & Santek, SSEC, Univ. of Wisconsin

Voxel-based imaging, where we're essentially looking at a continuous transparent density, or fog, is very valuable because it gives you the whole density at once. It gives you everything at once and it shows you all the different intensity levels. It shows you the intense areas, the high values and the low values together.

FLUID DYNAMICS APPLICATIONS

Laurin Herr on camera
Volume visualization is also proving useful in fluid dynamics where it is being applied to both experimental and computational research.

Fluid Dynamics Experiments: NCSA

There is a well-established tradition of physical experimentation in fluid dynamics.

Direct observation of real-time events is essential to gather data, test hypotheses and confirm numerical simulations.

Rendering of PLIF Flowfield Images: Van Cruyningen, Lorenzo & Hanson, Stanford Univerisity

In one of the newer experimental techniques, a laser beam is formed into a thin sheet of light by a lens and passed through a flowfield which fluoresces as a result. An image of the florescent gas at that instant is captured by a CCD camera and stored on a computer.

A time sequence of these images can be played back to study flow development.

A volume visualization can be created by stacking these 2-D images with time as the third dimension. This makes the flow evolution more apparent and allows easier comparison between frames.

The volume generated by this view of the developing flow can also be rendered as an opaque surface for further study.

The same apparatus can capture actual 3-D data sets. This is a volume visualization of the first vortex in the pulsed jet flow seen previously.

Of course, once the volume is created, it can be rotated to change the viewing angle.

And finally, this animation reveals the different concentration levels within the vortex, further demonstrating the versatility of volume visualization for studying multi-dimensional data sets with either time or space being the third coordinate.

Exposing a Mixing Flow: Wu, Sun Microsystems & Snyder, Stanford University

These unfolding contour surfaces show the world's first measurements of a fluid flow obtained with instantaneous 3-D optical tomography. A short pulse of laser light recorded the concentration of a cylindrical argon-helium jet flowing upward into air. The folding and extension of these surfaces display the convective mixing within the experimental volume.

Cosmic Jets: Kamrath & Elvins, San Diego Supercomputer Center

Radio telescopes have discovered "cosmic jets" of radiation moving through space. Some of these jets are inexplicably "bent" and scientists are trying to explain why.

Theory suggests that the jets are bending around big clouds of cooler, denser plasma. Only a 3-D computer simulation can represent such effects accurately, and the best way to see the results is by volume visualization.

Turbulent Shear Flow: Craig Upson, Stellar Computer

This is a polygonal surface representation of a turbulent shear flow. The simulation was calcluated on a 50-by-40-by-100 cell grid.

Here is a volume rendering of just the turbulent interface along the shear plane using the same data. Color and opacity variations show that mixing is not confined to a narrow region in space and that the thickness of the mixing layer is far from uniform, facts that were not apparent in the surface representation.

PPM Fluid Dynamic Simulation: Porter & Woodward, U. of Minnesota

This is a 2-D visualization of a 2-D simulation of the convective instability of compressible gases as might be found on the surface of the sun. Color is used to indicate the speed and direction of vorticity.

Here the initial conditions used in the 2-D simulation are replicated and stacked to make a 3-D grid which is then randomly perturbed. As this volume visualization reveals, convective mixing in 3-D yields a significantly different organization from what was seen in the previous two-dimensional example.

The fluid dynamics simulation underlying this visualization took 250 Cray hours. There are 500 time steps, each holding fifty megabytes of 3-D data. You're looking at 25 *gigabytes* of supercomputer output in each of these animation sequences. Yet even more computation at higher resolutions will be required to determine if the flow is truly chaotic, or if there is some new form of 3-D organization in this structure that is not yet understood.

ENGINEERING APPLICATIONS

Laurin Herr on camera
As with fluid dynamics, engineering applications can use either scanned or computed volumetric data.

Turbine Blade: Failure Analysis Associates

Non-destructive testing and failure analysis engineers use scanners to look inside manufactured objects in much the same way doctors use scanners to look inside patients.

Opaque Auto Cylinder Head: Failure Analysis Associates

The biggest difference is that the objects are often made of metal or some other dense material,

Transparent Auto Cylinder Head: Pixar

and as a result, the industrial CAT scanners use much more powerful X-ray beams.

Green Pipe: Failure Analysis Associates

In some cases, ultrasonic scanners are used instead, but the basic visualization process is the same.

Helicoptor Rotor Boot: Failure Analysis Associates

The goal is always to find the minute internal cracks or material flaws within that can't be seen from the surface, and yet could cause the part to fail.

F.E. Material Stress Tests on Aluminum Beverage Cans: Welling, PSCC

Computed mechanical structural analysis based on finite element methods has been widely applied for over thirty years.

Vessel Damage Control Simulation: John Winston, Rockwell Intl., AMSD

Graphics display techniques for the interpretation of computed mechanics, including the display of volumes, have been in development for almost as long.

James Winget on camera
Volumes are crucial in finite element analysis because the real world is in three dimensions. You can't engineer in Flatland. And that's true both for the computations that you have to do as well as exploring the results of those computations.

Stress Analysis Examples: James Winget, Silicon Graphics, NASA Ames Research Laboratory

It's not sufficient to look at stress contours on the outer surface of a part; that is not where the anomalous behavior is likely to occur. Instead, it's important to understand the stress distribution throughout the entire interior of the part, and not just on its outer surfaces.

I think that it's crucial for the growth of volume visualization that the scientists, engineers, and physicians participate in the evolution of the algorithms.

Jim Winget on camera
It's crucial that the quantification of data being displayed appropriately fits the physics and the underlying mathematics of that data.

MOLECULAR MODELING APPLICATIONS

Laurin Herr on camera
This is the classic 3-D visualization of a molecule. People have been using this abstraction for hundreds of years.

Fluoropolymer Simulations: Capobianco-Cray, Dixon-DuPont

But if you want to model a real molecule, especially a complex one, you need a better tool. This is a long-standing problem, but one which volume visualization may fundamentally help solve.

Fred Brooks on camera
Volume visualization is important in molecular modeling because the basic data that we get about much of the structure of most molecules is crystallographic data. And what that yields is the time average of the positions of the electrons in the molecule; and this is just fundamentally a cloud of varying densities. There are many methods of trying to identify which part of the cloud stands for which atom. And that's called "fitting the molecular model into the electron density map."

Electron Density Map: Fred Richards, Yale University

Laurin Herr off camera
Before computer graphics, the best visualization method in this field involved contour maps of electron densities mounted on Plexiglas sheets,

Richards' Box: Fred Richards, Yale University

and stacked in an apparatus called a Richards' Box, after the chemist who invented it. A half-silvered mirror, tilted at 45° to the viewer, allowed a brass model of the molecule, built at the lower front, to be visually superimposed onto the electron density maps, backlit and mounted in the upper rear.

Here's what the user saw. Everyone, including the inventor, agreed it was awkward to use. But it was the best 3-D visualization technique available at the time.

GRIP 75: Computer Science Department, UNC at Chapel Hill

Computer graphics offered molecular scientists a new set of tools that were quickly adopted. Here we are seeing one of the earliest systems which "opened for business" in 1975 at Fred Brooks' lab in Chapel Hill.

A key issue then, as now, was how to represent the volume of the electron cloud. This is an example of the so-called "basket-contouring technique."

Point Clouds: T.J. O'Donnell, EVL, University of Illinois at Chicago

Another technique, mentioned earlier, is point clouds, preferred by some even today for its compact data structure, fast display characteristics and non-explicit representation of surfaces.

AZT: Fred Deck, EVL, University of Illinois at Chicago

The point cloud concept has recently been updated by researchers at the Electronic Visualization Lab in Chicago who have placed small, transparent, reflective spheres at every point on an isocontour to more strongly convey a sense of a space-filling volume.

Tryptophan: Goodsell & Pique, Research Institute of Scripps Clinic

Molecular biologists at the Research Institute of Scripps Clinic are now producing volume visualizations like this:

DNA: Olson, Goodsell & Pique, Research Institute of Scripps Clinic

Here the surface is defined as an electron density cutoff value with higher density levels inside, color-coded and revealed by clipping.

SOD: Olson, Goodsell & Pique, Research Institute of Scripps Clinic

In this animation, electrostatic potential levels are shown as a variable transparency volume. Every frame shows a progressively lower isocontour value.

Bovine SOD: Olson, Goodsell & Pique, Research Institute of Scripps Clinic

Here the electron density map derived from x-ray crystallography is directly rendered with volume visualization, eliminating the need to create a geometric model.

Surfaces are isocontours of specific electron density ranges. Overlaps indicate chemical bonds.

Arthur Olson on camera
Volumes are a progression beyond surfaces in a number of ways, and part of that has to do with my motivation for getting into volume rendering and trying to explore its value.

HIPIP: Olson, Goodsell & Pique, Research Institute of Scripps Clinic

One of them is that the model is now somewhat separate from the rendering. You're talking about a representation that is inherently three-dimensional, whereas a surface is constructed in a three-dimensional world, but it's in essence a two-dimensional abstraction. So in that sense I think that volume rendering is a logical progression just conceptually.

Arthur Olson on camera
When one can start to think of the data as volumes rather than necessarily surfaces or connectivities, one has another realm in which one can look for patterns.

NOTE:
The last visualization showed the electron orbitals of the HIPIP molecule calculated from first principles. Such theoretical calculations were previously difficult to assess. This volume visualization helped clarify the structure of the cluster of four iron atoms and four sulfur atoms found in many proteins.

MATHEMATICALLY-DEFINED VOLUMES

Laurin Herr on camera
Volume visualizations can also be generated directly from mathematical functions without ever filling a 3-D-array of voxels.

Hypertextures: Ken Perlin, New York University

Here's something really new: hypertextures -- space filling textures.

A hypertexture becomes texture and shape, both at the same time.

These hypertextures were created using the concept of band-limited noise and therefore, should be classified as mathematically-defined volumes.

This is what happens if the frequency of the noise function is doubled while its amplitude is cut in half --

-- and again.

This one is made by summing the base textures of the previous three. Effectively, it becomes a fractal.

This one is made by doing a volume intersection, which is to say a multiplication, between a cubic-shaped density function and the fractal sphere we've just seen.

Quaternion Extension: John Hart, EVL, University of Illinois at Chicago

This is a three-dimensional Julia Set, a class of fractals. To be more precise, this is the quaternion extension of the single complex Julia Set.

It is defined as a set of points in a volume that don't escape to infinity when the function associated with them is iterated, or fed back into itself, forever. This clearly makes it a mathematically-defined volume.

Each frame reportedly required a teraflop of computation.

Detailed explanations of both hypertextures by Ken Perlin and quaternions by John Hart can be found in the SIGGRAPH '89 Proceedings.

VOLUMES vs. GEOMETRY
VOXELS vs. POLYGONS
SOME QUESTIONS ABOUT TERMINOLOGY

Laurin Herr on camera
We said earlier that volume visualization starts with the concept of a volume data set, commonly composed of voxels in a n-by-n-by-n lattice. Let's pursue this discussion a little further.

Chart: Volume Data Set vs Geometric Data Set

We contrasted traditional geometric data sets with volume data sets.

Chart: Isocontouring
Cervical Vertabrae Surface Rendering: Harlyn Baker, SRI International

We've seen numerous examples like this one that used isocontouring or some other method to extract a polygonal surface from the voxels, and then displayed that surface using one of the surface rendering techniques of traditional computer graphics.

Chart: 3-D Scan Conversion
Teapot: Arie Kaufman, Visualization Laboratory SUNY Stony Brook

Here is the converse example. A traditional computer graphics object, the classic teapot defined with Bezier patches, undergoes 3-D scan conversion to voxels and is rendered directly from the voxels.

Chart: Surface Rendering vs Volume Rendering

So, there's geometric data, made up of polygons. And when polygonal surfaces are rendered, it's called "surface rendering." When volume data, made up of voxels, is converted into polygons for rendering, it's also called "surface rendering."

Conversely, when voxels are rendered directly as voxels, or when polygons are converted to voxels and rendered directly as voxels, it is *usually* called "volume rendering."

Laurin Herr on camera
I say "usually" because, in a field as new as volume visualization, not everyone is using the same jargon yet. Alvy Ray Smith has something important to add here.

Alvy Ray Smith on camera
One very common way to represent a volume of information is geometrically. For example, we could define a volume as being all the space enclosed in a sphere of a given radius. The other path of volume visualization is where the data base is defined in terms of samples of a volume of space taken on a regular grid perhaps.

Now, I propose that, just to keep the terminology straight in our discussion, that the conversion of a geometrically-described volume into a computer picture be called "volume rendering," because we have traditionally, for fifteen years, used the term "rendering" to mean the conversion of a geometrically-defined surface data base into a computer picture. And this is just the volume generalization of that idea.

On the imaging side, let's call it "volume imaging." I should say on a sampling side, let's call it "volume imaging," because the most -- again, using the old 2-D terminology in generalizing with the 3-D -- the most common use of sampling theory in computer graphics in the last twenty years has been image processing, an image just being a sampling of a continuum, a photograph typically. And a whole variety of algorithms and techniques have evolved over these decades to manipulate samples on a computer screen in 2-D. Volume imaging is just a 3-D generalization of those sampling techniques to volumes to be converted into 2-D pictures.

Chart: Sampling Domain vs. Geometric Domain

Laurin Herr off camera
Here's a schematic version of what Alvy just said. And these, according to Alvy, are the 2 paths of volume visualization: in the sampling domain, leading to volume imaging; and in the geometric domain, leading to volume rendering.

Laurin Herr on camera
A common terminology would accelerate further development of volume visualization. However, it appears that more debate required before a consensus can be reached.

Chart: Volume Rendering Definition

In this report, we use the the term "volume rendering" to mean the direct display of voxels without any intermediate conversion of voxel data to polygonal surfaces before rendering to the screen.

ALGORITHMIC CHOICES

Laurin Herr on camera
The volume visualizer often has a choice between displaying data as a surface rendering or as a volume rendering. Both have their advantages.

Regional Oxidant Models: Whitted & Westover, Numerical Design, Ltd.

These visualizations were created from the same original data, a 42 x 60 grid in three layers, measuring ozone concentrations at various altitudes over the northeastern U.S. Turner Whitted's company produced them for the Environmental Protection Agency.

Turner Whitted on camera
What we've found is that the volume rendering seems very appropriate for exploratory work and especially used by the scientists themselves, while the surface rendering is especially useful for presentation purposes.

Chart: Volume Visualizaton Algorithmic Choices

Laurin Herr off camera
If the visualizer chooses to use volume rendering, what are the alternatives?

There are currently two basic approaches, as outlined here. Terms listed under one another are often used interchangeably.

Let's go back to Alvy Ray Smith to learn about the Alpha buffer algorithm pioneered by Pixar.

Alvy Ray Smith on camera
I guess one of the crucial things that we've done is that we've added this notion of partial transparency at every volume sample point so that you can see through the volume. You can also control the relative amounts of transparency to get different visualizations.

Upper Chest: Elliot Fishman, Johns Hopkins Hospital

What's not so straightforward and not so well understood is that the sampling of the original data has to average bone, muscle, air and fat at each sample. And what Pixar's algorithm does is take that into account; that it's not either fat or bone or muscle or air; it's some weighted combination of those tissue types.

Alvy Ray Smith on camera

Pixar's volume imaging algorithm works like this: Think of the volume of data being laid out in front of your eye, okay? So we're going to look at planes that are perpendicular to the line of sight, or parallel with the display screen.

We start with the plane of data which is farthest away. Okay, paint it into the picture. Then we bring in the next frame and we don't paint it in. We merge it in with the plane that's already there, using our alpha channel, which basically lets us composite one picture with another, allowing partial transparencies. In other words, colors behind can show through colors in front.

Now that's in your image and you bring in the next plane of information and merge it with what's already there and you bring in the next plane. And since our hardware happens to be ferociously fast at merging two-dimensional frames together, we can bring one of these complete volume visualizations up in a matter of seconds.

Marc Levoy on camera

Traditionally, the notion of displaying three-dimensional data has involved the simple hidden surface algorithm. You only display something in front and you remove everything that's behind. Once you have all of the data in its original form, you can begin to think about doing more subtle forms of the hidden surface algorithm, such as including transparency. And that's essentially the key to, for example, Pixar's volume rendering. They're trying to present more of the data by using a more subtle form of the hidden surface algorithm. That's one way to look at it.

Red Skull: Marc Levoy, University of North Carolina at Chapel Hill

Visually, the images that my algorithm produce are roughly the same as those of Pixar. The main difference is in the algorithm. They take their voxels and they throw them up onto the screen, what you might call an object order approach, whereas I start from the observer position and I trace rays though the data. And that would be called an image order approach.

Marc Levoy on camera

The tradeoffs between the object order and the image order approach is [that] Pixar, which throws their voxels onto the screen, can build hardware and firmware and microcode that takes advantage of coherence between the voxels. In other words, they can design a very fast box that just takes voxels and throws them up onto the screen. Whereas the image order approach doesn't take advantage of those kinds of optimizations, but it can take advantage of certain optimizations that have to do with the image plane. And so it allows different kinds of optimization. Theirs [is] primarily hardware optimization and my image order approach [is] primarily software optimization.

Craig Upson on camera
Ray tracing has the traditional limitations of aliasing artifacts. You know, when you sample this three-dimensional object now according to the resolution of the screen, that's essentially all the resolution you have. So as the object rotates you get aliasing artifacts, because in ray tracing, the rays diverge. You know, rays emanate at a point; they go through a two-dimensional plane, which is a screen, and they diverge in three-space. So you end up missing cells in the computational domain. On the other hand, the forward mapping, or the object space methods, tend to suffer less from those artifacts. But they can also be very slow, depending on how you use them.

Dan Sandin on camera
Well, the eventual tradeoffs of these two methods are yet to be found out, because presently it seems to take more computation to do the Z-buffering approach than it does to do the ray-casting approach. However, the Z-buffering approach has the potential of being put into firmware and hardware much like the Z-buffer has advantages over ray-tracing in hardware implementations.

Laurin Herr on camera
The debate over the best approach is only beginning. The Pixar and Levoy algorithms are not the only ones that exist. More recently, Lee Westover, working with Turner Whitted, published a variation on the object ordered approach, which Turner explains.

Turner Whitted on camera
What we do is we take each point in three-dimensional space and do a three-dimensional reconstruction of a continuous signal based on that point. Then we re-sample the continuous signal to give us an image that's free of aliasing artifacts or any other kind of sampling artifact.

Transluscent Head: Lee Westover, Numerical Design, Ltd.

Because of the order in which we're implementing the algorithm, we're able to do the reconstruction on a per sample basis independently and retain the parallel implementation.

Electron Density Cloud: Lee Westover, Numerical Design, Ltd.

Secondly, because we're eventually going to create an image in two dimensions, we can actually flatten the reconstruction process and do it in two dimensions in a way that speeds up the overall process.

Turner Whitted on camera
We call this flattening and reconstruction process "splatting." That's a term that Lee Westover devised. He uses the analogy of throwing a snowball at a brick wall and having it spread.

Laurin Herr on camera
"Splatting" is such an intriguing metaphor that we just had to try it. The concept is that each voxel has a density value. The "snowball" represents the region of effect of that voxel's unit of density on the final image. "Splatting" should reduce this 3-D region of effect to a 2-D region, making it easier to compute. Optimal "snowball" size is 1 -2/3 voxels. Here goes!

SPLAT!

VISUAL PERCEPTION AND INTERACTIVITY

Laurin Herr on camera
So far, we've talked mainly about the power, versatility and technology of volume visualization. What about its problems? Two of the biggest turn out to be directly related: interactivity and visual perception.

Fred Brooks on camera
I think in volume visualization the fundamental "seeing" task is itself difficult. So if one imagines a volume that consists of 4,000 cubes of different colored Jellos, the question of where is the green cube in the middle of all this is a hard "seeing" task, whether you do it with computer graphics or with real Jello. If you're doing it even with real Jello, the first thing you would do is try to move your head around and look at it from different points of view.

Mike Keeler on camera
The problem is how to look inside an object. Transparency gives you one technique, but you may have too many transparent objects and they all start blending together. Cutting planes are very useful so you throw away a lot of things forward and so you can look into the middle. That gives you the advantage of looking in, but it gives you the disadvantage of throwing away some things. And they're just different techniques. The important thing is to be able to interactively select these things -- to put cutting planes in interactively and move them around, rather than forcing you to make an *a priori* decision where those cutting planes should be.

Henry Fuchs on camera
With volume visualization we're faced with the problem that even if we had the most perfect image of the best possible scientific illustrator, we would not be able to understand what is there if we just had a painted image. We need a better understanding of where the various pieces of data lie in depth. And so I think we will need more work on increased depth cues. Stereopsis and head motion parallax are the ones that I think are going to be most promising.

Marc Levoy on camera
Interactivity, in my opinion, is absolutely paramount to volume visualization. Again and again I've had a physician sit down in front of one of my volume rendered images and look at it and say, "Well, that looks like a pretty image, but what am I really looking at?" And I'll hit a key and start rotation of a precomputed cine loop, which is all we can do nowadays, and the physician will say, "Oh, that's what I'm looking at." And, to me, this says that motion is essential, because they don't know what they're looking at until the thing moves.

Dan's Dots: Dan Sandin, EVL, University of Illinois at Chicago

Laurin Herr off camera
Here's a little example created by Dan Sandin to explain how important a role motion can play in human pattern recognition. Now you see it, now you don't.

HARDWARE ISSUES

Laurin Herr on camera
Volume visualization data sets can grow to enormous size. They require massive amounts of memory to hold them, high-performance CPU's to traverse them, and high bandwidth communications to move them around.

Spinning Logo: Silicon Graphics

Current workstations are, in general, optimized for fast polygon and vector processing, not volume visualization.

Rising Tracer Balls: Stellar Computer

Even the very high performance models can only handle relatively low resolution volume data sets at relatively low speeds. This significantly limits progress.

Brain Visualization: Richard Weinberg, USC and Ardent Computer

The point to remember is that volume data sets grow with the cube of their resolution. That is, doubling the linear resolution requires eight times more memory.

Henry Fuchs on camera
Volume visualization brings with it a host of computation problems that are significantly different than the previous kinds of visualizations we have done. Let me give you one example of it. The first, most obvious one, is that the size of the data set is no longer more compact than the final image.

Building: Hewlett-Packard
Piston: Silicon Graphics
Auto: Tektronix
Polygonal Chrysler: Hewlett-Packard

So, for instance, before volume visualization, when we dealt with buildings and automobiles and little balljoints that we were designing, the representation for those objects was by and large more compact than the final image, because we might have a representation for, say, an automobile in 50,000 little triangles, whereas we want it to have 1-1/2 million points in the end. And so there was an explosion of data from the compact representation to the final image.

Evolution of Structure in the Universe: Joan Centrella, Drexel University, Craig Upson, Stellar Computer

With volume visualization, this thing turns upside-down. We may have 100 million data points to start with and only one million final points.

Henry Fuchs on camera
And so the kind of architectures that we have developed very often are based on the previous assumptions where we have a compact representation. And in volume visualization, they no longer are as relevant because this assumption has now been broken.

Turner Whitted on camera
Look at the magnitude of storage that we're dealing with. If I have a 100-by-100-by-100 cube -- that's a megabyte -- a nice round number. Now let's say I want to deal with one hundred time slices of that. Now one hundred megabytes fits on a disk very nicely. I have no problem so far. What I really have problems with is getting that thing from my file server to my visualization workstation in a reasonable amount of time. I would like a little bit faster network to go along with it. But let's look at a different problem. And that is, where did that data come from? Well, that data came from the heart of the supercomputer and has been displayed on a workstation that's separated by some distance. Then I've got a worse problem. I've got to get that data out of the supercomputer into my workstation in a reasonable amount of time. I have the communications bandwidth problem. I have the problem of managing that data in the workstation. Presumably, I don't have that problem with storing that data in the supercomputer. I assume that it has infinite speed and infinite size -- by and large true from the visualization standpoint. So there are serious needs in that domain that aren't met by current off-the-shelf items.

Tom DeFanti on camera
One of the problems of volume visualization is that, just as raster graphics ground us to a stop in terms of real time interactive graphics in the early '70's and then we slowly climbed out of that hole to the fact [place] where we can do as many polygons in real time perspective, clipped and everything, as we could do vectors back in the early '70s. Now we're suddenly stopped, and we can't do volume visualization in real time. All we can do is this sort of semi-interactive steering. We can't ask all the questions that we want to in real time. And that, I think, is the frontier. That frontier clearly will be cracked by parallelism, massive parallelism -- we're talking Connection Machine-type tech that allows us to put thousands of processors. I often dreamed of the "smart pixel" where every pixel would have its processor. And now I want a "smart voxel," where every voxel has its processor and knows what its neighbor is doing, and so on. That, I think, is the frontier that we have to get across to get back to real time interactive, and then it's really going to be exciting.

Send in the Clouds: Geoffrey Gardner, Grumman Data Systems

FUTURE VISIONS

Mike Keeler on camera
The future of volume visualization is wide open right now. There are a lot of smart people working on it because it's an interesting area. There's brand-new things coming up all the time. It's a real exciting time. I can't foresee what algorithms are going to come up. I think people are going to try to apply the standard graphic things more and more to them. I think there's going to be faster hardware, so we can get more interactive speed. But primarily I think it's now at the realm where it's going to be started being used by real people. And toolbuilders and algorithm developers are going to get more feedback from the real users. And that will really spur more development.

Fred Brooks on camera
Start with a vision of what you want and I think we have not yet done enough thinking about what it is one wants to see on volume data. And it is not clear to me that there's one answer to that.

Shuttle Airflow: Ardent Computer

So computational fluid dynamics, where you have a fluid flowing around an airplane wing,

Blue Knee: Vincent Argiro, Vital Images, Inc.

probably needs a different way of visualizing it than a medical model, where there are really surfaces, called tissues, separating the organs from one another and not just a continuum of velocity.

Electron Density Visualization: Mosher & Johnson, Sun Microsystems, Inc.

And that's probably a different answer yet from an electron density cloud for around a molecule.

Fred Brooks on camera
So I think the different applications will require different kinds of visualizations.

Alvy Ray Smith on camera
Why should we even be interested in volume visualization, or what's the big deal? I mean, you could ask this question about pictures in general. What's the big deal?

And I think in either case, whether it's 2-D or 3-D, all it boils down to [is] people want to talk to each other in the most efficient, effective way.

Freddie: Elliot Fishman, Johns Hopkins Hospital

Same thing goes through for volume visualization, but now we're talking about something we're not used to talking about, which is visualizing things which can't be visualized -- the insides of human beings,

Downdraft Turbulence: NASA Ames

air flow over wings, et cetera. I mean, I can't even hardly say the words to you, but if I could show you the -- the belief is if I could show you a volume visualization of air turbulence over wings, I could say it without having to say words.

Alvy Ray Smith on camera
I could tell you my thought without saying any words, and I could do it instantaneously in the time it takes you to see the picture.

Closing Montage

Thunderstorm Simulation: Wilhelmson, NCSA
Golden Woman: Meinzer, German Cancer Research Center
White Face: Kaufman, SUNY / Stony Brook
Seismic Data Cube: Westover, Numerical Design,Ltd.
Water Droplet In Benzine Tube: Mosher & Johnson,
Blue AZT Molecule: Fred Deck, EVL, UIC
Quaternion Extensions: John Hart, EVL, UIC

Laurin Herr off camera
Volumes are a major addition to the fundamental visualization vocabulary. They enrich many of our classical techniques, and provide improved tools to grapple with the complex problems that will confront us as we move into the next century.

The ability to generate 3-D images without geometric models is perhaps the most distinctive technical feature. The fact that a single set of visualization tools can now be used for both scanned and computed data sets is a real advantage from a developer's point of view.

Laurin Herr on camera
In the long run, though, I believe the most significant aspects will prove to be conceptual elegance and general purpose applicability, for these will attract people to volume visualization. And people *are* the key. Thank you.

VOLUME VISUALIZATION

STATE OF THE ART

APPENDIX A

SPEAKERS' BIOGRAPHIES

Vincent Argiro
Vital Images, Inc.

Vincent Argiro is founder and chairman of the board of Vital Images, Inc. and currently holds an appointment as associate professor in the Department of Physiological and Biological Sciences of Maharishi International University, Fairfield, Iowa. Dr. Argiro received his B.A. in biology from Yale University in 1977 and his Ph.D. in neural sciences from Washington University in St. Louis in 1983. He is principal investigator on grants for instrumentation development for biological research from the National Science Foundation and the Iowa Department of Economic Development. Dr. Argiro has published research in the area of developmental neurobiology, is a recognized pioneer in computerized microscopy and has been pursuing the application of computer graphics technology to scientific visualization for over twelve years.

Frederick Phillips Brooks, Jr.
University of North Carolina at Chapel Hill

Frederick Brooks is Kenan Professor of Computer Science at the University of North Carolina at Chapel Hill, where he founded the computer science department in 1964 and was its chairman for two decades. Prior to coming to Chapel Hill, he worked for IBM for eight years, during which time he was a development manager for the IBM System/360. Dr. Brooks received his Ph.D. in applied mathematics (computer science) from Harvard University in 1956. He currently serves on the National Science Board and IBM's Science Advisory Committee. Dr. Brooks received the Distinguished Service Award of the Association for Computing Machinery in 1987, and the National Medal of Technology in 1985. He is the author of *The Mythical Man-Month: Essays of Software Engineering*, as well as numerous other books and technical papers.

Thomas DeFanti
University of Illinois at Chicago

Thomas A. DeFanti, Ph.D., is a professor of electrical engineering and computer science at the University of Illinois at Chicago, where he serves as the director of the Electronic Visualization Laboratory, and an adjunct professor at the National Center for Supercomputing Applications. DeFanti is an international lecturer and author in the computer graphics field, has created many interactive installations in museums and conferences worldwide, and serves on the editorial boards of several publications. He served as the chair of ACM SIGGRAPH from 1981 to 1985, and he has acted as editor-in-chief of the *SIGGRAPH Video Review* since its inception in 1980. He was vice-chair of the NSF-sponsored Panel on Graphics, Image Processing, and Workstations (and co-editor of its report *Visualization in Scientific Computing).* Most recently, he received the 1988 ACM Outstanding Contribution Award, was appointed to the Illinois Governor's Science Advisory Committee (GSAC), and was named a University Scholar for 1989-90. He received his Ph.D. in mathematics from Ohio State University.

Nick England
Sun Microsystems Inc.

Nick England is currently director of Visualization Products at Sun Microsystems Inc., located in Raleigh, North Carolina. He was previously the president of Transcept Systems, which was acquired by Sun Microsystems Inc. in May 1987. Transcept Systems developed the TAAC-1 Application Accelerator, which plugs into Sun Microsystems workstations and is designed for applications in graphics, image processing, and analysis. Prior to this venture, England was the vice-president of Graphics Terminals for Adage, Inc. He was previously the founder and president of Ikonas Graphics Systems Inc., which was acquired by Adage, Inc. in 1982.

Henry Fuchs
University of North Carolina at Chapel Hill

Henry Fuchs is Federico Gil Professor of Computer Science and adjunct professor of radiation oncology at the University of North Carolina at Chapel Hill. He received his Ph.D. in computer science in 1975 from the University of Utah. Fuchs is also a member of the technical advisory board of Stellar Computer Inc., a firm manufacturing high-performance graphics workstations. He is the principal investigator for research projects supported by the Air Force, DARPA, NFS, and NIH, most of which involve the development of high-performance 3-D graphics systems and algorithms for radiology, radiation therapy, and other medical applications.

Laurin Herr
Pacific Interface Inc.
New York, N.Y.

Laurin Herr has worked in the computer field since the mid-1960's and has consulted to Japanese, European, and American companies since the late 1970's. He founded Pacific Interface in 1980 as an international consulting company, developing an extensive network of professional contacts in Japan and elsewhere through his work on industrial study missions, international conferences, special events, industry and market research projects, and other consulting assignments.

Herr produced and directed a series of video and text reports on computer graphics with Raul Zaritsky that were published by Frost & Sullivan in 1986 and 1987. These were followed in 1988 by the 160-minute report entitled "Visualization: State of the Art," published as Special Issue 30 of the *SIGGRAPH Video Review*, and its update, Issue 35.

He has served as the official liaison with Japan for ACM SIGGRAPH since 1982 and was appointed to the International Relations Committee of the National Computer Graphics Association (NCGA) in 1987. Herr received a Bachelor of Arts degree in government from Cornell University in 1972. He pursued additional studies in Japanese language, history and politics at Cornell, and Sophia University in Tokyo.

Bill Hibbard
University of Wisconsin at Madison

Bill Hibbard is a researcher at the Space Science and Engineering Center (SSEC) at the University of Wisconsin. He received a B.A. in mathematics in 1970, and a M.S. in computer science in 1974 -- both from the University of Wisconsin. His current research interest is interactive computer graphics and image processing for earth sciences. He is a member of ACM SIGGRAPH, SIGArt, and the IEEE Computer Society.

Xiaoping Hu
University of Chicago

Dr. Hu is currently a research associate in the Department of Radiology at the University of Chicago. His research interest includes medical image processing and display and medical image reconstruction. He received his B.S. in physics from the University of Science and Technology of China in 1982, his M.S. in physics from the University of Chicago in 1984, and a Ph.D. in medical physics specializing in medical imaging from the University of Chicago in 1988.

Michael Keeler
Ardent Computer Corp.

Mike Keeler is director of scientific visualization at Ardent Computer Corp. He is responsible for the design and development of high level software tools for scientific and engineering users. The main emphasis of this work is to integrate computational applications with graphics and imaging in an easy-to-use and extensible framework. Special attention is given to techniques for visualizing volumetric datasets.

Previously, he headed up the Graphics and Animation Group at the San Diego Supercomputer Center, a NSF-sponsored facility designed to support a nationwide network of academic and industrial users. He has held several research positions at Scripps Institution of Oceanography and the University of California.

He graduated from the University of California at San Diego with degrees in visual arts and economics.

Marc Levoy
University of North Carolina at Chapel Hill

Marc Levoy is a research assistant professor of computer science and radiation oncology at the University of North Carolina at Chapel Hill. He received a B. Architecture in 1976 from Cornell University, a M.S. in 1978 from Cornell, and a Ph.D. in computer science in 1989 from the University of North Carolina at Chapel Hill. He was principal developer of the Hanna-Barbera Computer Animation System and served as its director from 1980 through 1982. His research interests include scientific visualization, texture mapping, volume rendering, medical imaging, and molecular graphics.

Arthur J. Olson
Research Institute of Scripps Clinic

Arthur J. Olson currently holds the Anderson Research Chair in the Department of Molecular Biology at the Research Institute of Scripps Clinic, where he is also Director of the Molecular Graphics Laboratory. Dr. Olson's research centers around the development and application of computational and computer graphic methodology to the study of biological macromolecules. His focus is on protein-protein interaction in such systems as virus particles and immune complexes.

Dr. Olson received his Ph.D. in physical chemistry from the University of California at Berkeley for work on computational methodology in x-ray crystallography. He was then awarded a postdoctoral fellowship to work at Harvard University, where he participated in mapping the first atomic resolution structure of a spherical virus particle. He then returned to Berkeley where he was a staff scientist at Lawrence Berkeley Laboratory and assistant director of the NSF-sponsored National Resource for Computation in Chemistry.

Stephen M. Pizer
University of North Carolina at Chapel Hill

Stephen Pizer is a professor of computer science, radiation oncology, and radiology at the University of North Carolina. He heads the multidepartmental Medical Image Display Research Group and co-leads Computer Science's Graphics and Image Laboratory. He received his Ph.D. in computer science from Harvard University in 1968. His current research covers human and computer vision, interactive 3D graphics, contrast enhancement, and workstation development. He works closely with laboratories in the Netherlands and Germany, and is an editor with *IEEE Transactions on Medical Imaging*.

Daniel J. Sandin
University of Illinois at Chicago

Daniel J. Sandin is a professor of art in the School of Art and Design and co-director of the Electronic Visualization Laboratory at the University of Illinois at Chicago. His early interest in computer graphics/video, image processing and interactive computing environments motivated his pioneering work in video synthesizers and continues to influence his research efforts in the field of 3-D phscolography today. Sandin's award-winning computer/video art has been exhibited worldwide. He has received grants and fellowships from such distinguished organizations as the Rockefeller Foundation, the Guggenheim Foundation, and the National Endowment for the Arts. In addition, his work is included in the inaugural collection of video art at the Museum of Modern Art in New York.

Alvy Ray Smith
Pixar

Dr. Alvy Ray Smith has lectured widely and published numerous technical papers in the field of computer graphics and computer animation. He received his Ph.D. in cellular automata theory at Stanford and was introduced to the field of computer graphics at Xerox PARC (Palo Alto Research Center). He worked with Ed Catmull at the New York Institute of Technology, where he wrote a paint program which was sold to Ampex and then converted into the first commercial paint system. Smith then moved to the computer division of Lucasfilm, where he worked again with Catmull, an effort that culminated in the introduction of a prototype of the Pixar Image Computer. This became the first product of the new company Pixar, co-founded in 1986 by Catmull and Smith.

Ulf Tiede
University Hospital Eppendorf
Hamburg, West Germany

Ulf Tiede is a researcher at the Institute of Mathematics and Computer Science in Medicine at the University Hospital Eppendorf, Hamburg, West Germany. The focus of his research is 3-D display techniques in medical imaging. Along with the chairman of his department, Professor Karl-Heinz Hoehne, Tiede works on the development of their 3-D display package and technique, Voxel Man. Tiede graduated from the University of Hamburg in computer science.

Craig Upson
Stellar Computer

Craig Upson is a visualization scientist at Stellar Computer. His academic background is in numerical mathematics from the University of New Mexico. He worked at Lawrence Livermore National Laboratory for seven years, performing three-dimensional computational fluid dynamics research along with the development of computer graphics algorithms for the computational sciences. After leading the scientific visualization effort at Digital Productions, a phase-1 National Science Foundation Supercomputing Center, Mr. Upson worked as a research scientist at the National Center for Supercomputing Applications at the University of Illinois, Urbana-Champaign. At NCSA, he organized the Scientific Visualization project along with Nancy St. John. His current duties at Stellar Computer include the design of visualization environments for computational scientists and engineers.

Turner Whitted
Numerical Design, Ltd.

Turner Whitted was educated at Duke University, receiving a B.S.E.E. degree in electrical engineering in 1969 and an M.S.E.E. degree the following year. He was granted the Ph.D. degree in electrical engineering by North Carolina State University. For the next five years, Whitted was a member of the Computer Systems Research Laboratory of Bell Laboratories. While at Bell Labs, he developed the simple and elegant algorithm that made ray tracing more efficient and widely usable, as first shown in his 1979 film "The Complete Angler." Returning to North Carolina in 1983, he became the founder and president of Numerical Design, Ltd., a firm which produces image rendering software. Since 1982, he has been an adjunct professor of computer science at the University of North Carolina at Chapel Hill. In 1986, Turner Whitted received the ACM/SIGGRAPH Computer Graphics Achievement Award.

James M. Winget
Silicon Graphics

Jim Winget is the principal scientist in research and development at Silicon Graphics, currently working on visualization tools for science and engineering, especially as they relate to the next generation of graphics workstations. Prior to this, he was the director of applications software at Silicon Graphics. He spent 1985-6 at Duke University, first as a consultant in the Divison of Radiation Oncology, and later as a research assistant professor in biomedical engineering.

Dr. Winget received his M.S. and Ph.D. in applied mechanics from the California Institute of Technology. He has consulted to Hewlett-Packard Laboratories, Lockheed Missiles & Space Co., Failure Analysis Associates, and Raychem Corp., among others.

VOLUME VISUALIZATION
STATE OF THE ART

APPENDIX B

IMAGE CREDITS

All image credits are listed in the order of their appearance.

Opening Montage

Red Skull
Marc Levoy
University of North Carolina at Chapel Hill

Electron Density Cloud
Lee Westover
Numerical Design

Voxel-Man
K. H. Hohne, M. Bomans, A. Pommert, M. Reimer,
U. Tiede, G. Wiebecke
Institute of Mathematics & Computer Science in Medicine
University Hospital Eppendorf
Hamburg, F.R.G.

American Clouds
Bill Hibbard & Dave Santek
SSEC, University of Wisconsin

Three-Toed Sloth
Chuck Mosher & Ruth Johnson
Sun Microsystems, Inc.

Chromosome
Harlyn Baker
SRI International

Earthquake Simulation
Thinking Machines Corporation
Visualization by: James B. Salem, Karl Sims, Hubert Delaney, John Richardson,
Peter Mora, Creon Levit (NASA AMES)

Chalice Sequence
James Blinn
JPL

Tin Toy

Direction, Animation & Story: John Lassiter
Technical Directors: William Reeves, Eben Ostby
Additional Animation: Willliam Reeves, Eben Ostby, Craig Good
Modeling: William Reeves, Eben Ostby, John Lassiter, Craig Good
Sound: Gary Rydstrom, Sprocket Systems
Production Coordination: Ralph Guggenheim, Susan Anderson, Deidre Warin
RenderMan Team: Jeffrey Mock, Jeff Hilgart, Tony Apadaca, Jim Lawson, Darwyn Paschey, Pat Hanrahan, Sam Leffer
"The Price Is Right": Courtesy Mark Goodson Productions © 1988 Price Productions
Very Special Thanks: Ed Catmull, Alvy Ray Smith, Bill Adams
Very, Very Special Thanks: Steve Jobs
© 1988 Pixar

Cube's Transformation

Conceived & Directed by: Ron Resch
Visual Data Base Design: S. Connelly, M. Cosman, C. Loop, N. Taylor, S. Zimmerman
Evans & Sutherland

Thunderstorm Simulation

Craig Upson, Stellar Computer, Inc.
Special Thanks to Stephan Fangmeier, Michael Keeler, Ian Reed
In Collaboration with the NCSA Scientific Visualization Program

Inner View

Software & Animation: Karl Sims
Special Thanks to Thinking Machines Corporation
Jim Salem, Lew Tucker, Herbert Delaney, Dana Fritsche
Thanks to Michael Halle, M.I.T. Media Lab
Music by: Richard Horowitz and Susan Deihim

Interaction of Cosmic Jets with an Inhomogeneous Intergalactic Matter

Anke Kamrath and T.Todd Elvins
San Diego Supercomputer Center
David De Young
Advanced Scientific Laboratory
Kit Peak National Observatory

Brain Peel
Hans Peter Meinzer
German Cancer Research Institute
Heidelberg, F.R.G.

Visualization of Simulated Treatment of Ocular Tumor
Wayne Lytle
Cornell University, CNSF

Mouse Embryo
Eihachiro Nakamae
Hiroshima University

Visualization of the Brain
Arthur Toga
Neuro Imaging Laboratory
UCLA

Radiation Therapy Simulation
George Sherouse
Medical 3-D Display Team, Depts. of Radiation Oncology and Computer Science
North Carolina Memorial Hospital - Chapel Hill

Mr. Yorick's Skull Gets Ahead in Life
Erica Liebman
GRASP LAB, University of Pennsylvania
Voxel Research: Samual Goldwasser, R.A. Reynolds

Hips
Pixar
Elliot K. Fishman
Department of Radiology, Johns Hopkins Hospital

Density Slides
Rotating Skull
Lung
Bronchial tubes
Elliot Fishman
Department of Radiology, Johns Hopkins Hospitals

Brain
Chuck Mosher & Ruth Johnson
Sun Microsystems, Inc.
Data: Shaw

Integrated 3-D Display of MRI and PET Images of the Brain
David N.Levin, Xioaping Hu, Kim K.Tan, Simranjit Galhotra
Departments of Radiology, Radiation Therapy and Neurology
University of Chicago Hospitals

Voxel-Man
K.H. Hohne, M. Bomans, A. Pommert, M. Reimer, U. Tiede, G. Wiebecke
Institute of Mathematics & Computer Science in Medicine
University Hospital Eppendorf
Hamburg, F.R.G.

Volume Microsopy of Biological Structures
Vincent Argiro
Vital Images, Inc.

Beating Heart and Blood Volume
Shigeki Yokoi
University of Nagoya, Japan

Beating Heart in Chest
K.H. Hohne, M. Bomans, A. Pommert, M. Reimer, U. Tiede, G. Wiebecke
Institute of Mathematics & Computer Science in Medicine
University Hospital Eppendorf
Hamburg, F.R.G.

Inner View
Software & Animation: Karl Sims
Special Thanks to Thinking Machines Corporation
    Jim Salem, Lew Tucker, Herbert Delaney, Dana Fritsche
Volume Data Courtesy:
    Van Wedeen, Massachusetts General Hospital
    Peter Kijewsty, Brigham Woman's Hospital
    Mike Statcher, Harvard Medical School
Thanks to Michael Halle, M.I.T. Media Lab
Music by: Richard Horowitz and Susan Deihim

Point Clouds
T.J. O'Donnell
Electronic Visualization Laboratory
University of Illinois-Chicago

Bubble Man
Norman Badler
University of Pennsylvania

Metaball Man
Koichi Omura
Osaka University
TOYO Links

Fractal Landscapes
Richard Voss,
IBM T.J. Watson Research Center

Particle Dreams
Karl Sims
Optomystic

Study of a Severe Thundestorm
Scientific Research: Robert Wilhelmson
National Center for Supercomputing Applications
University of Illinois, Urbana-Champaign

Seismic Slides
Paolo Sabella
Sun Microsystems, Inc.

Seismic Images
Chuck Mosher and Ruth Johnson
Sun Microsystems, Inc.

Send in the Clouds
Geoffrey Gardner, Eric De Mund & Bill Sakoda
Thanks to: Herb Tesser & Rob Kelly
Computer Graphics Laboratory, Grumman Data Systems

Hypertextures
Ken Perlin
New York University

Simulations of Compressible Convection with PPM
David Porter & Paul Woodward
University of Minnesota

Quaternion Extension
John Hart
Electronic Visualization Laboratory
University of Illinois-Chicago

National Hail Research Experiment
National Center for Atmospheric Research

President's Day Storm
Bill Hibbard & Dave Santek
SSEC, University of Wisconsin

Real-Time Interactive Visualization of Earth Science Data
Bill Hibbard & Dave Santek
SSEC, University of Wisconsin

Fluid Dynamics Experiment
Courtesy of NCSA

Rendering of PLIF Flowfield Images
I. van Cruyningen, A. Lorenzo & R.K. Hanson
High Temperature Gas Dynamics Laboratory
Stanford University

Exposing a Mixing Flow
Kevin Wu, Sun Microsystems, Inc.
Ray Snyder, Stanford University

Interaction of Cosmic Jets with an Inhomogeneous Intergalactic Matter
Anke Kamrath and T.Todd Elvins, San Diego Supercomputer Center
David De Young, Kit Peak National Observatory

Turbulent Shear Flow, Opaque Surface Rendering
Craig Upson, Stellar Computer
Data Courtesy of Michael Norman, NCSA

Electron Density Map
Richards Box
Fred Richards
Sterling Professor of Molecular Biophysiscs
Yale University

GRIP 75
Computer Science Department
University of North Carolina at Chapel Hill

Point Clouds
T.J. O'Donnell
Electronic Visualization Laboratory
University of Illinois - Chicago

AZT Molecule
Fred Deck
Electronic Visualization Laboratory
University of Illinois - Chicago

Trytophan
DNA
SOD
Bovine SOD
HIPIP
Arthur J. Olson, David S. Goodsell & Michael E. Pique
Research Institute of Scripps Clinic

Hypertextures
Ken Perlin
New York University

Quaternion Extension
John Hart
Electronic Visualization Laboratory
University of Illinois - Chicago

Teapot Volume Rendering
Arie Kaufman
Visualization Laboratory
SUNY Stonybrook

Send in the Clouds
Geoffrey Gardner, Eric De Mund & Bill Sakoda
Thanks to: Herb Tesser & Rob Kelly
Computer Graphics Laboratory
Grumman Data Systems

Shuttle Airflow
Ardent Computer

Blue Knee
Vincent Argiro
Vital Images, Inc.

Electron Density Visualization
Chuck Mosher & Ruth Johnson
Sun Microsystems, Inc.

Freddie
Elliot Fishman
Johns Hopkins Hospitals

Downdraft Turbulence
NASA Ames Research Center

Closing Montage

  Thunderstorm Simulation
  Robert Wilhelmson
  NCSA

  Ray-Traced Golden Woman
  Hans-Peter Meinzer
  German Cancer Reearch Center, Heidelberg

  White Face
  Arie Kaufman
  Visualization Laboratory
  SUNY / Stony Brook

  Seismic Data Cube
  Lee Westover
  Numerical Design, Ltd.

Purple Water Droplet in Benzene
Ruth Johnson & Chuck Mosher
Sun Microsystems, Inc.

Blue AZT Molecule
Fred Deck
EVL, University of Illinois - Chicago

Quaternion Extension
John Hart
EVL, University of Illinois - Chicago