Visualization
Expanding Scientific and Engineering Research Opportunities

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Computational science and engineering (CS&E) describes a researcher's use of computers to simulate physical processes. CS&E parallels the development of the two other modes of science: theoretical and experimental/observational.

In addition to new methodologies, new technologies or mathematical tools have spurred the scientific revolutions. For example, calculus allowed Newton to codify the laws of nature mathematically and develop analytic methods for solving simple cases. Similarly, the development of the von Neumann computer architecture gave scientists the ability to solve the discretized laws of nature for general and complex cases.

CS&E now relies heavily on scientific visualization to represent these solutions, enabling scientists to turn mountains of numbers into movies and graphically display measurements of physical variables in space and time. This article explores the convergence of science and visualization, in support of its successful growth and development.

What is scientific visualization?

Computer graphics and image processing are technologies. *Visualization*, a term used in the industry since the 1987 publication of the National Science Foundation report *Visualization in Scientific Computing*,[1] represents much more than that. Visualization is a form of communication that transcends application and technological boundaries.

Visualization holds great promise for computational science and engineering, provided we can meet the immediate and long-term needs of both toolmakers and tool users.

A tool for discovery and understanding. The deluge of data generated by supercomputers and other high-volume data sources (such as medical imaging systems and satellites) makes it impossible for users to quantitatively examine more than a tiny fraction of a given solution. That is, it is impossible to investigate the qualitative global nature of numerical solutions.

With the advent of raster graphics, researchers can convert entire fields of variables (representing density, pressure, velocity, entropy, and so on) to color images. The information conveyed to the researcher undergoes a qualitative change because it brings the eye-brain system, with its great pattern-recognition capabilities, into play in a way that is impossible with purely numeric data.

For example, an observer instantly sees the vortices, shock systems, and flow patterns in a visualization of a hydrodynamic calculation, while these same patterns are invisible in mere listings of several hundred thousand numbers, each representing field quantities at one moment in time. When computing a space-time solution to the laws of physics, the particular numeric quantities at each event in time-space are not important; rather, what is important is understanding the global structure of the field variables that constitute the solution and the causal interconnections of the various components of that solution.

A tool for communication and teaching. Much of modern science can no longer be communicated in print. DNA sequences, molecular models, medical imaging scans, brain maps, simulated flights

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through a terrain, simulations of fluid flow, and so on, all need to be expressed and taught visually over time. To understand, discover, or communicate phenomena, scientists want to compute the phenomena over time, create a series of images that illustrate the interrelationships of various parameters at specific time periods, download these images to local workstations for analysis, and record and play back one or more seconds of the animation.

According to the visualization report, "We speak (and hear) — and for 5000 years have preserved our words. But, we cannot share vision. To this oversight of evolution we owe the retardation of visual communication compared to language. Visualization by shared communication would be much easier if each of us had a CRT in the forehead."[1]

Our CRTs, although not implanted in our foreheads, are connected to computers that are nothing more than extensions of our brains. These computers, however, might not be in the same room with us. They could be down the hall, across town, or across the country. Hence, the ability to communicate visually — and remotely — with computers and each other depends on the accessibility, affordability, and performance of computers and computer networks.

The visualization report recommends the development of a federally funded initiative providing immediate and long-term funding of both research and technology developments (see Table 1).[1] Research developments are the responsibility of tool users — experts from engineering and the discipline sciences who depend on computations for their research. Technology developments are handled by toolmakers — the visualization researchers who can develop the necessary hardware, software, and systems.

Tool users' short-term needs

Every researcher requires a personal computer or workstation on his or her desk connected with a remote supercomputer. However, not all scientists require the same level of computing power. Hence, a three-tiered model environment is beginning to emerge that categorizes visualization systems by such factors as power, cost, and software support.

Table 1. Recommendations for a national initiative on visualization in scientific computing.

	Short-term Needs	Long-term Needs
Tool users: Computational scientists and engineers	Funding to incorporate visualization in current research	Funding to use model visualization environments
Toolmakers: Visualization scientists and engineers	No funding necessary	Funding to develop model visualization environments

Table 2. Visualization facility three-tiered hierarchy.

	Model A	Model B	Model C
Hardware	Supercomputer or super image computer	Minisupercomputer or image computer	Advanced workstations (mini-/ micro- image computer
Bandwidth (potential interactive rates, bits/second)	$>10^9$	10^7-10^8	10^3-10^6
Location (where users interact with the display screen)	Machine room (at the center)	Laboratory on a high-speed local area network	Laboratory on a national/ regional network
Software (in addition to discipline-specific data generation and processing)	Commercial packages for output only (no steering). Research required to develop interactive steering capabilities	Commercial packages are mostly output only. Some interaction is becoming available. Research required to improve discipline-specific interaction	Commercial packages and tools are widely available for both computation and interaction. Research required in languages, operating systems, and networking
Administration			
Strength:	Support staff	Discipline-specific visualization goals	Decentralization
Weakness:	Centralization	Small support staff	No support staff

Workstations. Researchers need workstations with access to supercomputers for

- immediate access to local graphics capabilities,
- networked access to supercomputers, and
- hard-copy recording.

Local graphics. Workstations, minicomputers, and image computers are significantly more affordable than supercomputers, and they are more powerful and effective visualization tools. There are already some 20 million personal computers and workstations in the United States, compared with about 200 supercomputers. Workstation users are increasingly treating supercomputers as one of many windows on the screen, and scientists must be able to "cut and paste" between the supercomputer and applications running on their local machines.

Access to supercomputers. Scientists need to transfer data to and from a main computation device, but today's networks are too slow for use in visualization. Some temporary techniques reduce the demand for high bandwidth, such as off-peak image transmission, image compression, image reconstruction from abstract representations, and local image generation. Networking is therefore as critical as computer power in helping scientists.

Hard-copy recording. Whether the visuals are for personal analysis, information sharing among peers, or presentations in formal surroundings, equipment for producing photographs, slides, videotapes, or laser disks needs to be in place and as easy to use as sending text files to a laser printer.

Scientists need the ability to create ad hoc graphics to verify the integrity of their simulations, gain insights from their analyses, and communicate their findings to others. Low-cost animation facilities should be connected to every user workstation so researchers can make scientific "home movies" with little effort. High-end visualization capabilities and facilities also should be available at all research centers; high-end graphics become important for presentation and publication of

Low-cost, visualization-compatible workstations and networks

Our ability to communicate visually and remotely with supercomputers and each other depends on

(1) the ease with which we can use our office/home computers to connect with the outside world, receive and transmit visual information, and record this information on videotapes or slides, and

(2) the cost/performance of today's networks.

The Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago is doing research in both areas. We are designing as our scientific animation workstation a low-cost computer system with a well-integrated visualization programming environment.

Users at the National Center for Supercomputing Applications (NCSA) — or any of the National Science Foundation-funded supercomputer centers, for that matter — cannot do graphics remotely due to slow network speeds, centralized and expensive graphics equipment, lack of graphics software tools, and the need for specialists in film/video production. Our research is motivated by the recent availability of low-cost graphics hardware and a good PC-based visualization toolkit, coupled with a growing awareness that scientists need visualization more for personal/peer analysis than for presentations.

EVL is integrating affordable commercial equipment with specially designed graphics software to make visualization a reality for computational scientists — whether they use their computers on a stand-alone basis or connected to supercomputers over networks. (Regarding affordability, academicians can generally receive $10,000 in equipment monies from their departments or colleges without applying for external grants — our yardstick is that equipment should cost no more than a three-year-old Buick.)

EVL's scientific animation workstation, shown in the accompanying figure, has hard-copy recording capability and an easy-to-use visualization environment to facilitate scientists' needs. The following list corresponds to items 1-6 in the figure.

(1) Supercomputer access. Supercomputers are most efficiently used to run complex simulation codes, the output of which is numbers. With access to graphics, researchers can convert numbers to pictures to qualitatively examine the global nature of their simulation output. Graphics can be made available on the host machine or, more efficiently, on the local workstation.

(2) Televisualization: graphical networking. As images require more colors, higher resolution, or larger volumes of data, they need more memory and become more impractical to transmit over networks or phone lines, to store on disks, or to convert and display on different frame buffers. EVL's Imcomp compression and conversion software converts images consisting of 24, 16, or 8 bits per pixel to 16 or 8 bits per pixel, then compresses them further to 2 or 3 bits per pixel while maintaining a reasonable full-color representation.[1,2] The program takes only 0.4 seconds to run on the Cray X-MP at NCSA, and it converts and transmits a 512 × 512 × 24-bit image from NCSA to EVL over a 56-kilobyte line within a few seconds.

Moreover, visuals must be transmitted from memory to memory (that is, from supercomputer memory to frame buffer memory in the local computer), not just from file to file as in electronic mail-type networks. NCSA's Telnet communications software has been modified to do this and expanded to include Imcomp routines that automatically compress images.

In addition to compression, value-added nodes speed up graphical transmission by balancing transmission costs with local computing costs. Model data is sent over networks and then rendered or reconstructed at the scientist's end. EVL is currently investigating the use of its AT&T Pixel Machine as a graphics server that would render model data transmitted over the network from the supercomputer and then transmit the resulting images over a local area network to individuals' desktop computers.

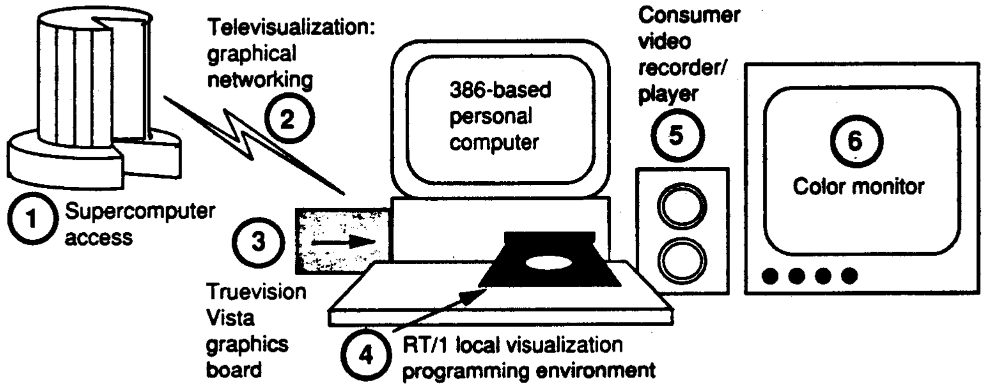
(3) Truevision Vista graphics board. Scientists need to be able to preview, record, and play back animations at any speed and in cyclical fashion to examine the dynamics of their data changing over time, to spot anomalies, or to uncover computation errors. The Vista board's large configurable memory allows us to get anywhere from 32 screens at 512 × 512 pixels to 128 results once researchers conclude their work.

Three-tiered model computational environment. Observations of the way scientists use visualization suggest that a three-tiered model environment is evolving, as defined in Table 2. Each model is distinguished by hardware costs, computing power, bandwidth, location, software support, and administrative considerations.[1]

This model environment assumes that scientists want as direct a visual connection to their computations as possible. While supercomputers (model A) provide scientists with powerful number-crunching tools for generating data, they currently do not produce graphics; they do fill arrays with information that somehow gets piped to display devices. (Table 2 assumes that supercomputers and super image computers have equivalent power. Super image computers, although not commercially available today except in the form of a special-purpose flight simulator, will provide the specialized processing necessary for real-time volume visualization.)

Workstations give scientists more control over their visual output (models B and C). A workstation typically addresses its display memory the same way it addresses regular memory, incurring essentially no hardware overhead to display computed results. (Table 2 also assumes that minisupercomputers and image computers have equivalent power, and that advanced workstations and mini-/micro- image computers have equivalent power.)

Scientists should be able to select either more-expensive workstations with powerful visualization potential (model B) or less expensive ones (model C) while maintaining network connections to larger machines (model A) to do computations when necessary. This interdependency can work quite well. For example, a scientist can calculate 20-60 frames of a simulation sequence on a supercomputer, download the images to a workstation to create a minimovie, and then play back the sequence at any speed under local control.[2,3] (See sidebar, "Low-cost, visualization-compatible workstations and networks.")



The Electronic Visualization Laboratory's RT/1 graphics language, an 80386-based personal computer, the Truevision Vista board, and consumer video gear comprise a scientific animation production facility that is economical enough to be made available to research scientists and engineers on a broad scale.

screens at 128 × 128 pixels, all at 8 bits per pixel. The board is also video compatible, so images can be recorded directly to videotape.

(4) Real Time/One (RT/1) local visualization programming environment. Scientists need a set of tools for picture composition, picture saving/restoring, fonts and text, resizing, rotation, moving, copying, hand retouching (painting), color manipulation, etc. They also need a local graphics programming environment in which to develop new tools or extend the capabilities of existing ones.

RT/1, an easy-to-use graphics programming language developed by EVL faculty and students, meets the criteria required of a visualization system environment. The language, written in C and running under Unix and MS-DOS, runs on all of EVL's workstations and personal computers. EVL is porting RT/1 to new workstations as they are acquired, extending the capabilities of the language, and developing application programs tailored to the needs of scientists.

(5) Consumer video recorder/player. If it's not recordable, it's not science. Moreover, the equipment for producing videotapes needs to be as easy to use as sending text files to a laser printer. We are integrating low-cost consumer video equipment into the workstation so scientists can quickly and easily preview and record frames of animation.[3] This equipment also comes with a built-in microphone so scientists can add narration or other sounds to visual recordings.

(6) Color monitor. Today's consumer video systems not only record but also can be attached to any television for immediate viewing of recorded material. Scientists can take a small video unit to a conference and plug it into a television there to share findings with colleagues. Should peers in other towns have similar equipment, colleagues could mail tapes to each other for viewing.

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Table 3. Total corporate computing needs. (Source: Larry Smarr, NCSA, Sept. 1988.)

	Computational Science and Engineering	Data Processing
Corporate officer responsible	Vice president of research or long-range planning	Vice president of management information systems (MIS)
Tiered architectures	Personal computers and graphics workstations; midrange machines (mainframes/minisupercomputers; supercomputers *Need exists for multivendor, networked, hierarchical computing.*	Personal computers; minicomputers; mainframes *Software portability only partially exists between these levels, and then only within one vendor's product line.*
	Open systems *No vendor has emerged who offers integrated systems and end-to-end solutions. As a result, end users are faced with a confusing set of products from various vendors and nowhere to turn for advice on how to integrate them.*	Closed systems *IBM and Digital Equipment Corporation manufacture all levels of computers and the connections between them.*
Vendors	Fragmented market populated by start-ups and extremely high-growth companies: Workstations (Sun, DEC, Apollo, IBM, Hewlett-Packard, Apple, Silicon Graphics, Ardent, Stellar, AT&T Pixel, etc.); Midrange (DEC, IBM, Alliant, Amdahl, Convex, Scientific Computing Systems, Multiflow, Elxsi); Supercomputers (Cray, IBM).	Mature, slow-growth marketplace dominated by a few giant vendors, such as IBM and DEC.
Operating Systems	Unix	MVS, DOS, VMS (proprietary)
Networking protocols; telecommunications; speeds	Open network standards; Long-haul telecommunications; High speed = 1,000 Mbits/second *Because of the scarcity of $20 million supercomputers, most universities and corporate CS&E users are remote and must gain access to supercomputers over long-haul telecommunication lines.*	SNA, DECnet (proprietary); High speed = 50 Mbits/second *Within a corporation, most networks hook many "dumb terminals" up to a central mainframe where all the computing power resides. PCs are generally used stand-alone; those networked to a mainframe generally use the network to download or upload files, and computing is decoupled.*
Common unit of information	Image (megabyte) *Supercomputer simulations produce such enormous amounts of data that visualization is essential.*	Number (byte)
Common unit for computation speed	Mflops	MIPS

Additional models D, E, and F, corresponding to personal computers, alphanumeric CRT terminals, and batch output, respectively, also exist. They do not represent advanced visualization technology, so they are not included in our model environment. Note, however, that model F has been used to produce a great deal of animation for both the scientific and commercial entertainment industries for the past 20 years.

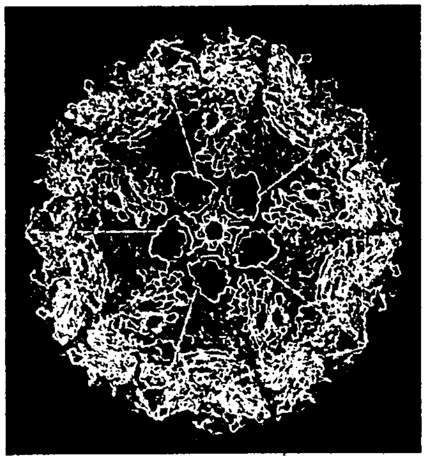
Tool users' long-term needs

CS&E is emerging as a new marketplace with needs distinct from those of data processing, as shown in Table 3. Success in the CS&E marketplace of the 1990s will depend on a commitment to standards, ease of use, connectivity, open systems, integrated systems, software portability, multivendor environments, leading-edge technology, and customer service and support.[4]

The list of research opportunities for visualization in scientific computing is long and spans all of contemporary scientific endeavor. The sidebar "Scientific and engineering research opportunities" presents specific examples of advanced scientific and engineering applications to show

(Continued on p. 22)

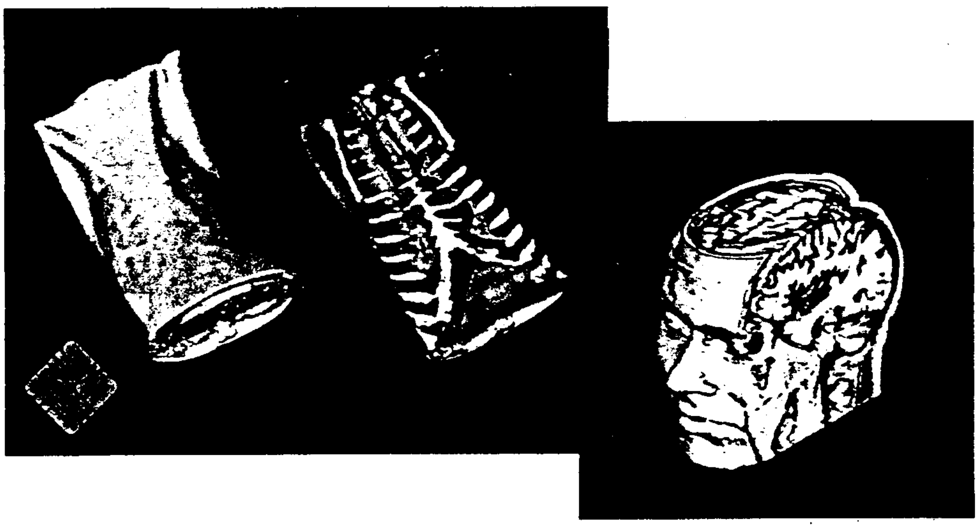
Scientific and engineering research opportunities



Molecular modeling. The use of interactive computer graphics to gain insight into chemical complexity began in 1964. Interactive graphics is now an integral part of academic and industrial research on molecular structures, and the methodology is being successfully combined with supercomputers to model complex systems. Two types of images can currently be generated: realistic pictures of molecules and 3D line drawings. Raster equipment is used to create realistic representations and animations, while vector hardware, used for real-time display and interaction, creates line drawings.

The image at left is a 3D line drawing of the rhinovirus, the common cold virus, showing its geometric structure and complexity. The image at right is an artistic rendering of the human papilloma virus (HPV). It was done by a group of Chicago-area artists who appreciate the underlying mathematics of nature and the complexity of the inner workings between atoms.[1]

Left-hand © 1988 T.J. O'Donnell. Data courtesy of Dr. Rossman, Crystallography Group, Purdue Univ. Image courtesy of the EVL, Univ. of Illinois at Chicago. Right-hand © 1989 $(\text{Art})^n$ Laboratory, Illinois Institute of Technology. $(\text{Art})^n$ artists: Donna Cox, NCSA, Univ. of Illinois at Urbana-Champaign; Stephan Meyers, Dan Sandin, and Tom DeFanti, EVL, Univ. of Illinois at Chicago; Ellen Sandor, $(\text{Art})^n$ Laboratory, Illinois Institute of Technology.

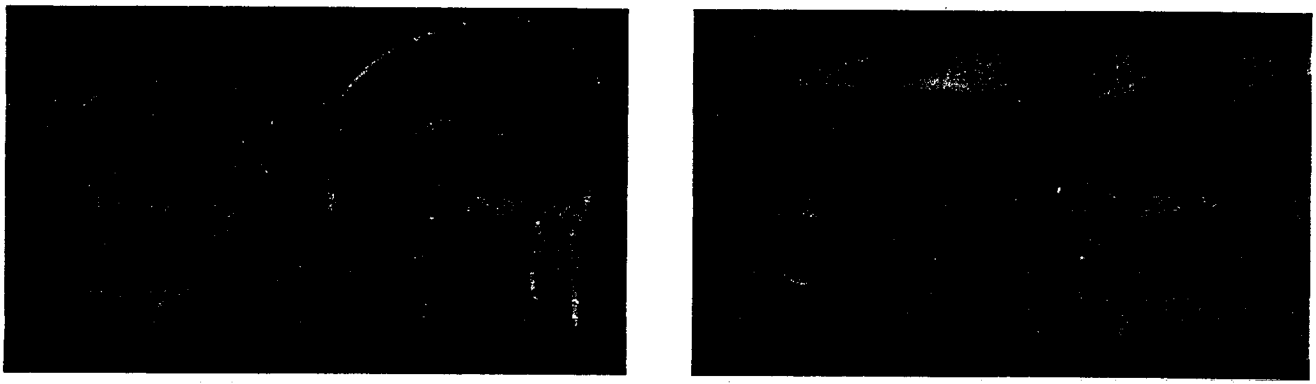


Medical imaging. Scientific computation applied to medical imaging has created opportunities in diagnostic medicine, surgical planning for orthopedic prostheses, and radiation treatment planning. In each case, these opportunities have been brought about by 2D and 3D visualizations of portions of the body previously inaccessible to view.

The above-left image is a shaded surface volume rendering of a 128 × 128 × 197 computerized tomography scan of a tree sloth. The opacity of various structures can be interactively modified to show the skin surface or to reveal internal structures. The bones of the rib cage, shoulder blades, and spine can be seen in the image on the right, as well as the trachea, lungs, heart and diaphragm.

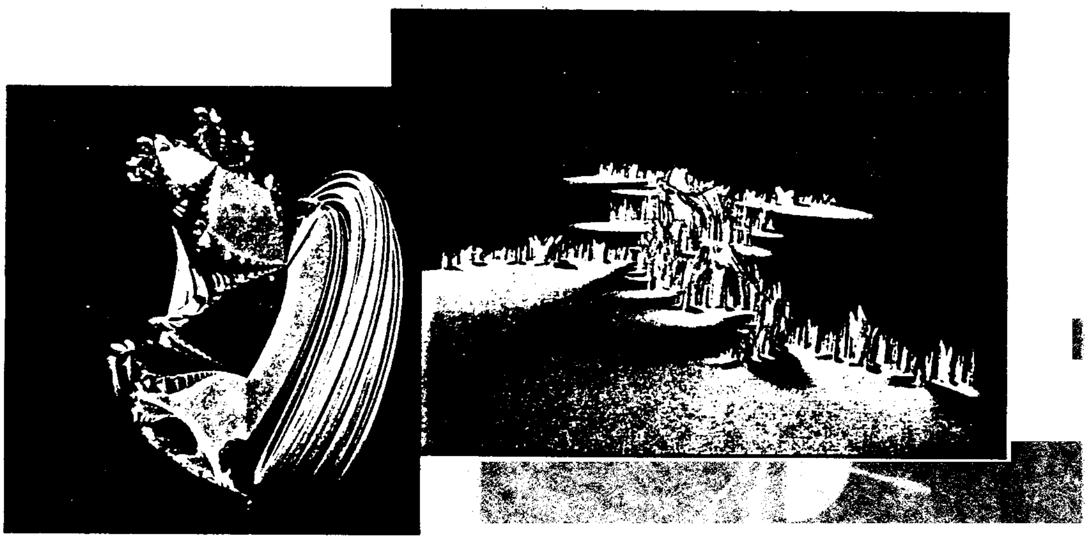
The above-right image is a shaded surface volume rendering of a 256 × 256 × 61 magnetic-resonance imagery (MRI) scan of a human head. The rendering shows a mixture of surface and slice-based techniques, where external structures such as the skin are rendered with surface shading, while slice planes are voxel-mapped to reveal the original MRI data. Physicians can use this technique to relate the position of internal structures such as tumor sites to external landmarks. These images were generated using the Voxvu volume rendering tool on a Sun workstation with the TAAC-1 Application Accelerator.

© 1989 Chuck Mosher and Ruth Johnson, Sun Microsystems. Data for above-left image courtesy of Eric Hoffman, UPA. Data for above-right image courtesy of Jeff Shaw, Vanderbilt Univ.



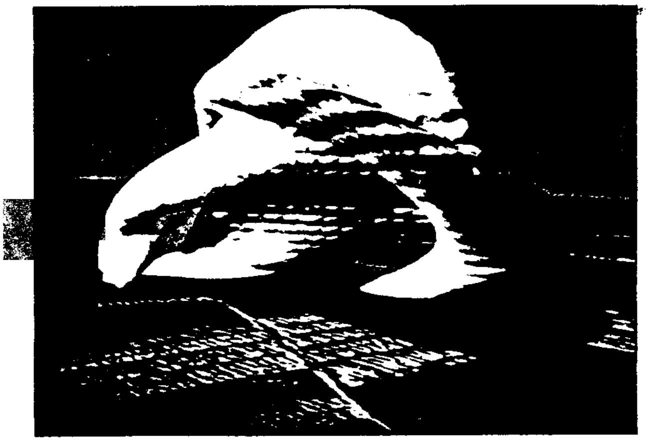
Brain structure and function. Rutgers University is using computer vision and visualization methods to automatically detect white-matter lesions in MRI scans of the human brain.

In the above-left image, low-level vision methods locate the outline of the brain, landmarks such as the interhemispherical fissure plane, and suspected lesions. The system calculates the orientation of the brain and uses the segmentations provided by the low-level methods to fit a deformable model to each patient's brain to determine the position and shape of difficult-to-identify organs or regions of interest. This customized model, shown in the above-right image, is used to obtain information about the anatomical position of the suspected lesions so that the system can reject false positives and determine the affected organs. The system has been tested on more than 1,200 images from 19 patients, producing good results.



Mathematics. These images illustrate a type of fractal known as the Julia set. A filled-in Julia set is a set of points that do not converge (or diverge) to infinity after repeated applications of a function, such as $f(z) = z^2 + c$. These functions are often investigated in the complex plane, but they also exist in the quaternions, a coordinate system that spans one real and three imaginary axes. Visualization helps mathematicians understand these equations, which are too complex to conceptualize otherwise.[2]

The above-left image is a quaternion filled-in Julia set minus its front-upper-left octant; the inner components of the four-cycle are revealed, defining its basin of attraction. The above-right image is a visualization of a dendritic quaternion Julia set in the complex plane; the unusual lighting uses a 3D gradient in the complex plane.



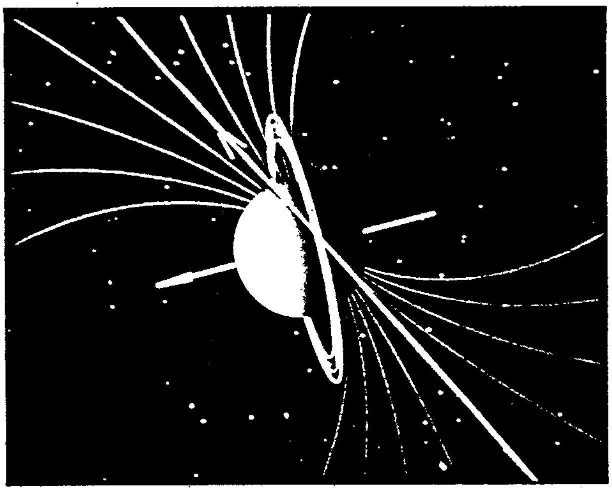
Geosciences: meteorology. The study of severe storms through observation and modeling helps research meteorologists understand the atmospheric conditions that breed large and violent tornadoes and the mechanisms by which tornadoes form and persist.[3] Theoreticians and field workers obtain information on behavior that cannot be safely observed; study the interactions of various environments, characterized by differing vertical wind, temperature, pressure, and moisture structures; and obtain useful guides for future research.

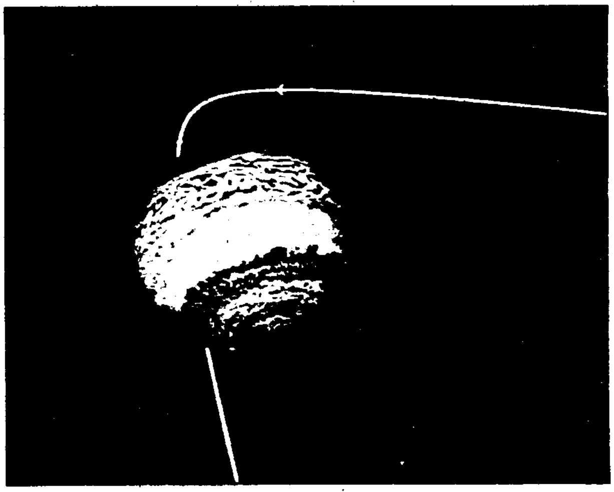
Transparency and volumetric rendering are used to view multiple surfaces; shading is used to display individual solid surfaces.

The above-left image uses voxel (grid cell) data to display rainwater and vertical vorticity information about a storm,[4] providing scientists with more information than if they had observed the storm with their eyes. The fuzzy region indicates low rainwater amounts while the bright white regions indicate large amounts of rainwater within the cloud. The vertical vorticity is texture mapped onto the rainwater with color; purple indicates dominant positive vorticity and blue indicates dominant negative vorticity.

The above-right image is from an animated simulation of a storm over Kansas, in which the rainwater surface was polygonized (tiled) and then rendered. The simulation clearly reveals substantial variations in the structure of the rainwater field not apparent earlier.

Above-left © 1988 Robert Wilhelmson and Craig Upson, NCSA, Univ. of Illinois at Urbana-Champaign. Above-right © 1988 Robert Wilhelmson, Crystal Shaw, Lou Wicker, Stefen Fangmeier, and the NCSA Visualization Production Team, Univ. of Illinois at Urbana-Champaign.

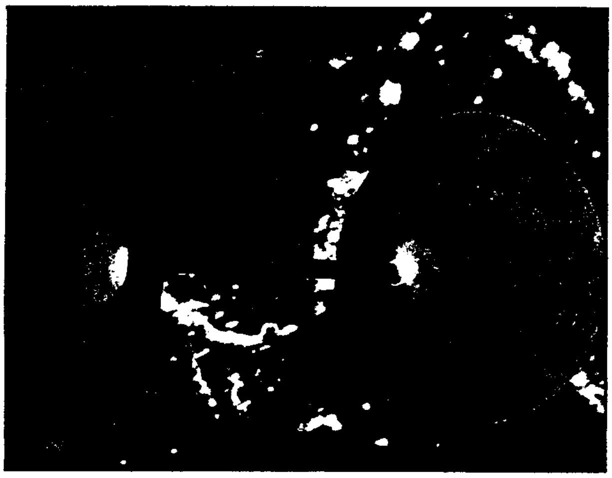


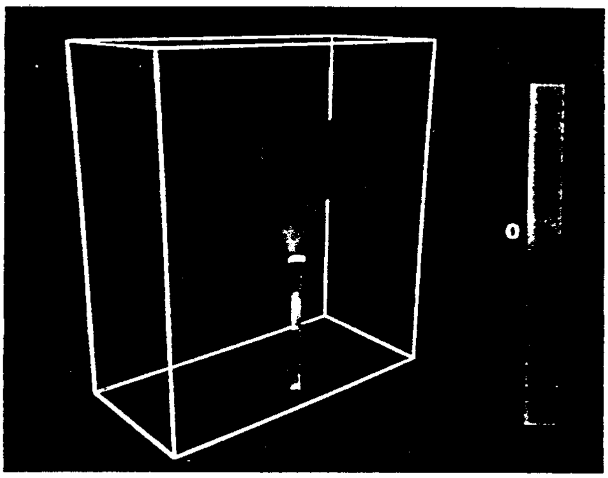


Space exploration. The field of planetary study involves the accumulation of huge volumes of data on the planets in the solar system. Enough data is now available that scientists are beginning to integrate observed phenomena and theory from other fields involved in planetary study: meteorology, geography, planetary physics, astronomy, and astrophysics.

The above-left image is from an animated simulation of the dynamics of Uranus' magnetosphere. The simulation shows that the angle of the dipole axis (purple arrow) is offset from the planet's angle of rotation (aqua arrow). The above-right image is from a simulation of the Voyager 2 Neptune encounter to occur in late summer of 1989. This image illustrates the path of the Voyager 2 as viewed from Earth.

Above-left © 1989 Computer Graphics Group of the Jet Propulsion Laboratory and G. Hannes Voigt of Rice Univ. Above-right © 1989 Computer Graphics Group of the Jet Propulsion Laboratory.





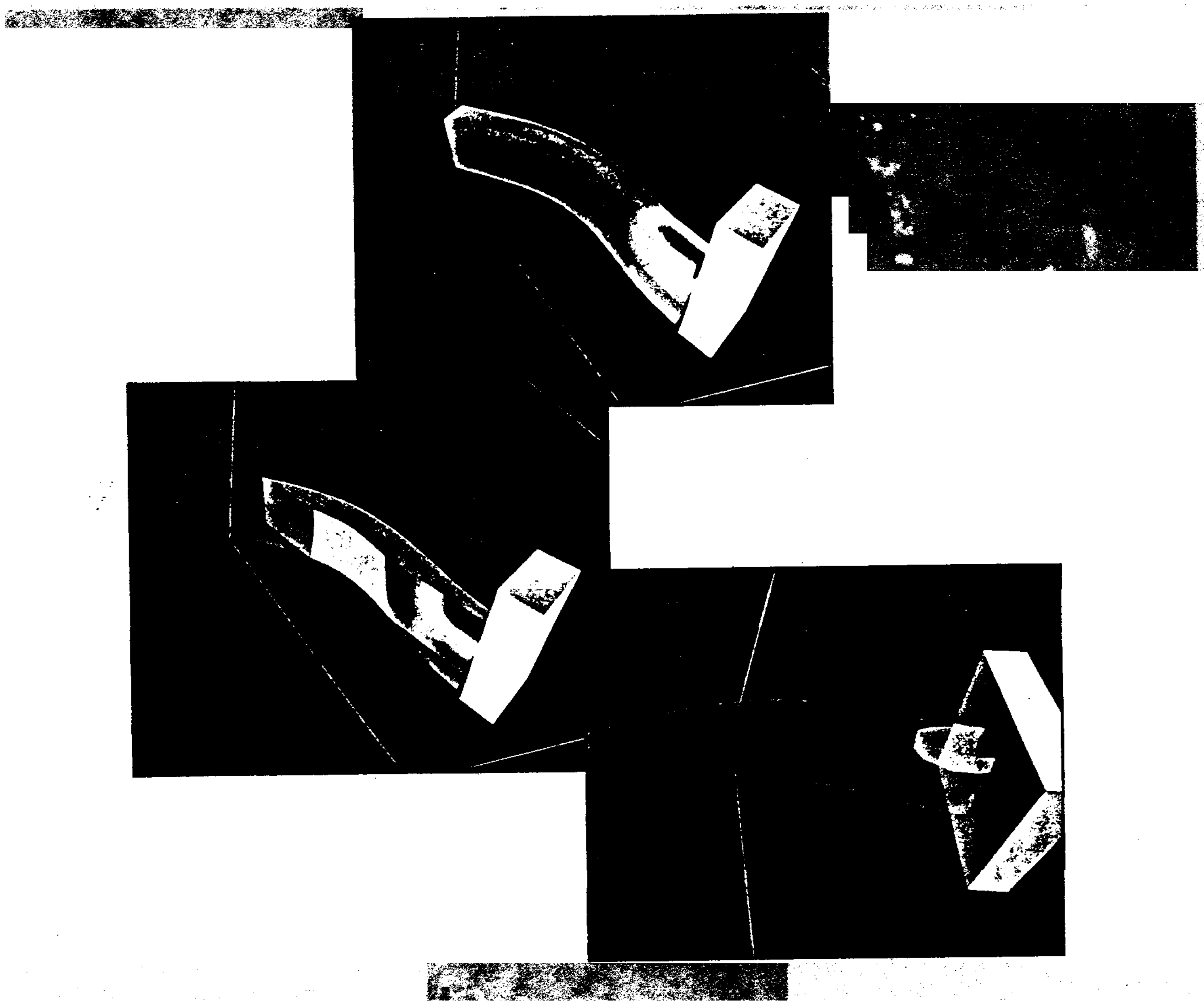
Astrophysics. Computational astrophysicists at the NCSA work with artists in an attempt to see the unseen and create visual paradigms for phenomena that have no known visual representation.

An embedding diagram of a Schwarzschild black hole and the behavior of its gravitational field, illustrated in the above-left image, was obtained from a numerical solution of Einstein's numerical relativity equations. The surface of the diagram measures the curvature of space due to the presence of the black hole, while the color scale represents the speed at which idealized clocks measure time (with red representing the slowest clocks and blue representing the fastest).

A black hole emits gravitational radiation after it has been struck by an incoming gravity wave. The above-right image is from an animated sequence that shows, for the first time, the influence of the curved space on the propagation of the radiation. Through the use of an isometric embedding diagram, the curvature of the space surrounding the black hole is represented by the surface on which the waves propagate. The white ring locates the surface of the black hole, and the regions above and below represent the exterior and interior of the black hole, respectively.

Computational fluid dynamics. Computational astronomers rely on supercomputing and visualization techniques to understand why jets from some galaxies flare dramatically. Magnetohydrodynamics code is used to solve equations that describe the flow of a fluid or gas with magnetic fields using finite differences.

The above image is a visualization of a cosmic jet traveling at Mach 2.5 passing through a shock wave (located at the left of the image). The jet abruptly slows and breaks up into a broadened subsonic plume whose morphology, or shape, is strikingly similar to that of a radio lobe of a wide-angle tailed galaxy. The morphology of the jet after impact is emphasized through the use of pseudocolor. This research has given astronomers important clues about why jets from some radio galaxies flare into broad plumes while jets from others remain remarkably straight and narrow.[5,6]



Finite element analysis. Finite element analysis is used in this example to show the stress distribution in a beam at its maximum tip displacement in the third eigenmode. The results were computed using linear elastic elements and a lumped-mass approximation.

The top image uses a conventional approach of displaying the stress values on the outer surface of the deformed shape. The middle image uses a cutting plane to look at the stress values on a cross section of the root of the beam. The bottom image shows a different view of the beam and uses an iso-contour stress surface to convey the three-dimensional nature of the stress concentration at the root of the beam. These images are still frames from fully animated and interactive models. They were computed and rendered on a Silicon Graphics 4D/120 GTX workstation using the SolidView program to perform real-time cutting and iso-contour surface generation.

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(Continued from p. 16)

how visualization tools are helping researchers understand and steer computations. Our examples fall into the following categories:

- Molecular modeling,
- Medical imaging,
- Brain structure and function,
- Mathematics,
- Geosciences (meteorology),
- Space exploration,
- Astrophysics,
- Computational fluid dynamics, and
- Finite element analysis.

Toolmakers' short-term needs

Commercial industry currently supports visualization hardware and software, as listed below. There is a pressing need to educate the scientific and engineering research communities about the available equipment.

Software. Commercial visualization software exists in the following categories:

Lines. The earliest software for graphics drew lines in three dimensions and projected them onto a two-dimensional plane, offered viewing transformations for looking at the result, and offered transformations (scale, rotate, and translate) for describing the line objects. The theory and practice of drawing lines, expressed in homogeneous coordinates, and the control and display of lines using 4 × 4 matrices, represented a major development in computer graphics.

A variety of current standards incorporate these basic principles, and the CAD/CAM industry has embraced this level of the art. It is cheap enough to put on every engineer's desk and fast enough for real-time interaction.

Polygonal surfaces. The next level of software — surfaces represented by polygons — has only recently been built into hardware. Polygon filling, or tiling, is commonly available in hardware and software. Hidden surface removal is included, and antialiasing of polygon edges is sometimes provided to remove distracting stairsteps, or jaggies. Light sources can be incorporated into the rendered image, but they are usually point sources at infinity emitting white light.

Patches. The next level of sophistication represents surfaces as curved surface pieces called patches. This is still largely a software domain, although we expect hardware to appear soon. The most advanced software packages handle a variety of patch types. They also provide very sophisticated lighting models with multiple-colored lights and distributed or point sources located either at infinity or in the scene.

Antialiasing is assumed, and the packages handle optical effects such as transparency, translucency, refraction, and reflection. Research software provides even more features that produce greater realism, such as articulated motion blur, depth of field, follow focus, constructive solid geometry, and radiosity.

The software contains no practical limit on scene complexity (such as the number of allowable polygons), but computation of highly complex scenes on a supercomputer can take anywhere from 0.5 to 1.5 hours per frame.

Image processing. Image processing software has followed a separate path over the last 15 years. The elaborate software packages now available provide functions such as convolution, Fourier transform, histogram, histogram equalization, edge detection, edge enhancement, noise reduction, thresholding, segmentation, bicubic and biquadratic warping, and resampling.

Many of these functions have been hardwired into special boards. General-purpose processors have only recently become powerful enough to make software competitive with hardware while maintaining generality. Image computers can run both computer graphics and image processing software packages.

Animation. In its broadest sense, animation means movement. It frequently connotes the complex motion of many objects, possibly articulated, moving simultaneously, and interacting with one another. Animation is desirable for the visualization of dynamic, complex processes. Basic animation control routines should be part of any standard visualization tool kit.

Glue. A class of software appreciated by visualization professionals but not necessarily by scientists is the "glue" used to combine images generated or analyzed by the packages described above. For convenience, a user must have tools for picture composition, picture saving/restoring, fonts and text, resizing, rotation, moving, copying, hand retouching (painting), color manipulation, etc. Together, these functions comprise a visualization environment system, which is to visualization what an operating system is to general computing.

Window systems. Windowing systems are commonplace in black-and-white bit graphics and are being extended to color graphics. Visualization software must incorporate and remain consistent with windowing concepts.

Volume visualization. Volume visualization software is still rudimentary. Algorithms for rendering lines, curves, surfaces, and volumes into volume memories are only now becoming available.[5,6] Hidden volume removal is unknown, the compositing of volumes is yet to be fully addressed, 3D paint programs (sculpting programs) have yet to be written, and general utilities for arbitrary rotation and size change of volumes do not exist. In other words, there is much research to be done in this field.

Hardware. The following are available commercial visualization hardware tools:

Input devices. Current digital input devices include supercomputers, satellites, medical scanners, seismic recorders, and digitizing cameras. The rapidly increasing bandwidth of these devices emphasizes the need for work in volume visualization.

We expect continued improvement in the resolution and bandwidth of input devices. Supercomputers will get faster and the resolution of images from satellites will increase. Real-time video digitizers already exist. Monochrome digital digitizers with 2,048 × 2,048-pixel resolution are becoming quite fast, although they do not yet operate at real-time speeds. Print-quality input scanners are still quite expensive, but we expect the prices to fall as digital technology cheapens and competing scanning technologies mature. CCD (charge-coupled device) array input scanners will improve in resolution and become serious candidates for input devices in high-resolution work.

Interactive input devices are continually improving. Common 2D devices include knobs, switches, pedals, mice, and tablets. Tablets are the most general and also reed the most improvement; they need higher resolution, higher speed, and more degrees of freedom.

Six-dimensional interactive devices are also available, providing the usual 3D positional information plus three degrees of orientation information (yaw, pitch, and roll). Higher-dimensional devices, such as the data glove, have begun to appear. These will improve to offer higher resolution, higher speed, and lower cost.

Output devices. Raster displays of 2D frame buffers have improved steadily to offer more colors, higher resolutions, and less flicker. A typical color raster display today offers a 1,280 × 1,024-pixel display at 60 frames per second and 24 bits of color per pixel (16 megacolors).

High-definition television (HDTV) — a proposed standard that will offer larger, brighter, sharper pictures than currently available in video — will affect visualization. Also, video is moving toward an all-digital format, designated 4:2:2, to standardize digital interconnections of diverse video products.

Color raster displays will evolve toward 2,048 × 2,048 pixels in the next several years. The displays themselves already exist in limited quantities, but the computational bandwidth required to feed them is still lacking. Black-and-white 2D raster displays already have resolutions greater than 2,048 × 2,048 pixels with enough bandwidth to feed them. These displays will certainly reach even higher resolutions in the next five years.

Stereo displays are also beginning to appear commercially, and we confidently predict that these will improve in screen size, resolution, brightness, and availability. These displays will be quite helpful in volume visualization.

Other output devices are similarly improving. HDTV will spur the development of compatible recorders. Film recorders will become cheaper as the technology becomes cheaper and the competition matures. Should stereo become a widely accepted mode of presentation for volume visualizations, then stereo film and video standards will have to be developed.

Workstations. Fast vector machines are now common and have extensive use in such areas as CAD/CAM and real-time 3D design. Recently, they have improved to offer color vectors and perfect end-matching. Frame buffers have been added so that surface raster graphics can be combined with vector displays.

Also, fast surface machines are about to arrive. They exist in simplified forms already and in more advanced states as firmware in special machines. Chips are now being built to speed up certain aspects of surface rendering, particularly the tiling of polygons. By 1990, full hardware support of surface graphics will be available, offering rendering features such as texture mapping, bump mapping, antialiasing, reflections, transparency, and shadows.

Vector machines will initially serve as powerful, real-time front ends to surface machines. Eventually, surface machines will be cheap and fast enough to permit scientists to do real-time design using surfaces rather than lines.

Among image processors, fast planar machines have existed for some time. These machines contain special boards for certain aspects of image processing, such as fast Fourier transforms. Faster versions are becoming available that have wider processing capabilities and higher resolutions. In fact, the notion of a general-purpose image processor that can implement any image processing algorithm as a program is becoming common.

Toolmakers' long-term needs

Raw computing power would be more effectively harnessed than it is today if calculations could be understood pictorially and their progress guided dynamically. Modern modes of computing involve interactive, extemporaneous generation of views from masses of data and exploration of model spaces by interactive steering of computations.

A scientist's ability to comprehend the results of his or her computations depends on the effectiveness of available tools. To increase that effectiveness, we need to

- encourage the production of documented, maintained, upward-compatible software and hardware;
- motivate manufacturers to solve network bottleneck problems;
- encourage universities to incorporate CS&E and visualization in computer science, engineering, and discipline-science curricula; and
- guarantee the publication and dissemination of research and results on a variety of media.

Hardware, software, and systems. General visualization issues that need to be supported include:

- Interactive steering of simulations and calculations
- Workstation-driven use of supercomputers
- Graphics-oriented programming environments
- Higher-dimensional visualization of scalar, vector, and tensor fields
- Dynamic visualization of fields and flow
- High-bandwidth picture networks and protocols
- Massive data-set handling, notably for signal and image processing applications
- Vectorized and parallelized algorithms for graphics and image processing
- Specialized architectures for graphics and image processing
- A framework for international visualization hardware and software standards

Networking. The application of networks to visualization, called *televisualization*, encompasses much more than text transfer (such as electronic mail) and gateway protocol decoding. It also involves image transfer, which entails compression, decompression, rendering, recognizing, and interpreting. Televisualization requires a major enhancement over existing network capabilities in the following areas:

Increased data rates. The sheer scale of graphics and imaging data sets challenges the current bandwidth and interactivity of networks. Networks handle screenfuls of textual information well; network nodes are simply gateways that neither add nor detract from the quality of the message. But a 512 × 512-pixel image with 8 bits per pixel has approximately 100 times more information than a screen of text with 25 rows and 80 characters per row. A 1,024 × 1,024 × 1,024-voxel volume with 48 bits per voxel contains 16,000 times more information than a 512 × 512-pixel image. Gigabit speeds are sufficient to pass volumes of the current size of 256 × 256 × 256 voxels with 4 bytes per voxel, but this rate will have to be extended within several years to 1-gigabyte/second channels.

Compression/decompression algorithms. Compression improves the speed with which visual data is transmitted. Current schemes for full-color image compression work well,[7] but other forms of compression must be researched, and comprehensive protocols must be developed for managing all these capabilities:

Table 4. The evolution of communication tools.

Communications media	Number of years old
Sight	5×10^8
Speech	5×10^5
Writing	5×10^3
Print broadcasting	5×10^2
Visual broadcasting	5×10^1
Visualization	5×10^0

- Transmit the procedures to create the images rather than the images themselves.
- Transmit endpoints of vector images.
- Transmit polygonal, constructive solid geometry, or bicubic patches of surface models.
- Transmit semantic descriptions of the objects.

Value-added processing at nodes. Value-added nodes also speed up graphical transmission. Computers process text and numbers in main memory, occasionally transmitting some of them to peripherals. Images, however, often must be transferred to special memories for rendering, 3D imaging, or viewing. Each instance of transferring and processing an image aims to increase its visualization value to the scientist. The ability to process images at various nodes along a network embraces the central concept of distributed processing.

In distributed computing, transmission costs are balanced with local computing costs. It sometimes makes more sense to send model data over networks and then render or reconstruct the data at the scientist's end. This presumes that there is appropriate equipment at both ends, that the various software modules are compatible with one another, and that the software can run on a variety of equipment types.

A televisualization network for image passing between machines is analogous to the software paradigm of message passing between process layers. This type of networking, combined with interaction, cannot be achieved using conventional Fortran subroutine calls. Significant software development and protocol standardization are necessary to bring televisualization to the discipline sciences.

Interaction capabilities. Interactive visual computing is a process whereby scientists communicate with data by manipulating its visual representation during processing. The more sophisticated process of navigation allows scientists to dynamically modify, or steer, computations while they are occurring. This lets researchers change parameters, resolution, or representation, and then see the effects.

Teaching CS&E and visualization. The principal barrier to growth in the CS&E market is the fact that corporate researchers and managers lack education and training in CS&E technologies and methodologies. Few industrial researchers know how to use distributed CS&E to do their work and, more importantly, they do not know how to think computationally and visually. Other roadblocks include the following:

- The Association for Computing Machinery's approved computer science curriculum lists computer graphics as merely one of many optional topics; image processing is not mentioned at all.
- Engineering accreditors do not require computer graphics or image processing.
- Many engineering school deans are unaware of the importance of visualization or cannot justify the hardware and software expense involved in teaching the subject.
- The number of tenured faculty teaching computer graphics in American universities is about the same today as 15 years ago, and they are roughly the same people.
- Scientists, while educated to read and write, are not taught to produce or communicate with visuals.

Publication and dissemination. Contemporary scientific communications media are predominantly language-oriented. Printed media are coupled weakly, if at all, to the visual world of space-time. By contrast, half the human neocortex is devoted to processing visual information. In other words, current scientific communication leaves out half — the right half — of the brain. An integral part of our visualization task is to facilitate visual communication from scientist to scientist, engineer to engineer, through visualization-compatible media.

Publication and grants, and therefore tenure, rarely come to researchers whose productivity depends on or produces visualization results. Superiors evaluate scholarly work by counting the number of journal articles published; publications are text, and visual media do not count. Funding itself is based on the careful preparation and evaluation of proposals, which are documents full of words and numbers.

As scientists depend more and more on the electronic network than on the printed page, they will need new technologies to teach, document, and publish their work. Until scientists can build on each other's work, productivity will lag. Publishing (specifically textual materials) has always been a critical part of this building process, and it is one of the primary bottlenecks in CS&E's progress.

Reading and writing were only democratized in the past 100 years. Today, they are the accepted communication tools for scientists and engineers. Table 4 shows that, in time, visualization will also be democratized and embraced by researchers.

Electronic media, such as videotapes, optical disks, and floppy disks, are now necessary for the publication and dissemination of mathematical models, processing algorithms, computer programs, experimental data, and scientific simulations. The reviewer and the reader need to test models, evaluate algorithms, and execute programs themselves, interactively, without an author's assistance. Similarly, scientific publication must extend to use visualization-compatible media.

The use of visualization in scientific computing — in academia, government research laboratories, and industry — will help guarantee

- US preeminence in science and technology,
- a well-educated pool of scientists and engineers with the quality and breadth of experience required to meet the changing needs of science and society, and
- American industries that can successfully compete in the international economic arena.

The information age has yet to deal with information transfer. Visualization technologies can help lead the way to better global understanding and communication. ☐

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