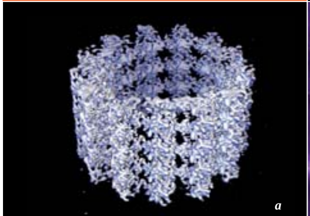
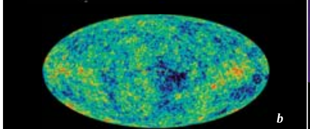
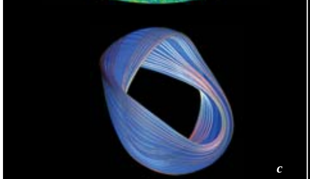
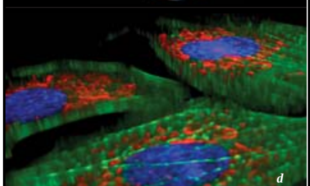
Foundations for
SCIENTIFIC LEADERSHIP

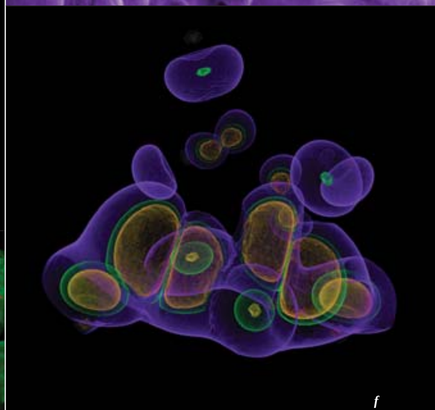
BEING THERE: INSTRUMENTS AND VISUALIZATION

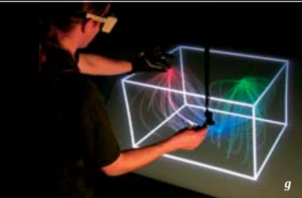


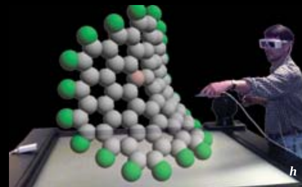


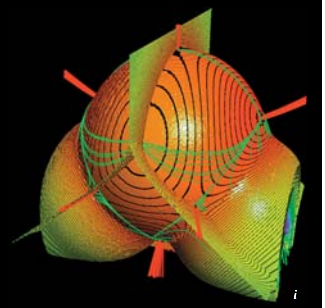












Information technologies pioneered in Federal research underlie the generation of highly sensitive diagnostic and research instruments now speeding advances throughout the sciences. These capabilities include the world's most powerful telescopes and instrumented satellites; magnetic-resonance imaging (MRI, which measures absorption of radio waves by tissue within a magnetic field), computed tomography (CT, an X-ray technique), and other non-invasive techniques for looking inside the body; electron, atomic-force, and other forms of microscopy and spectrometry that examine matter at the atomic level, and large-scale facilities that generate data about atoms by focusing concentrated light beams on them or creating high-speed particle collisions. All of these technologies are governed by IT hardware and software systems, with a top-layer software interface enabling human operators to manage the equipment and software components that translate measurements into digital data that can be displayed graphically.

Advanced visualization techniques developed through NITRD research have made it possible to render instrument data as high-resolution images in three dimensions, to show the dynamics of three-dimensional processes over time, to see and manipulate an image from all angles, and to generate sophisticated composites representing many layers of data.

Like modeling and simulation techniques, visualizations of data generated by state-of-the-art instruments are providing not just scientists but students and the public with views of the intricacy of matter at scales too tiny or too vast to be seen any other way. In biomedical research, for example, imaging is rapidly expanding knowledge about proteins, the complex biomolecules that are life's core workforce. Investigation of their genetically determined shapes and functions is a top national research priority today. Scientists believe these molecules hold the keys to revolutionary new treatments for human diseases and those affecting other species.

Remarkable bits of software-driven engineering in atom-scale microscopy instruments even make it possible for users not just to see the invisible world of atoms and molecules, but to physically maneuver and experiment with them. These inventions, which include IT-guided optical "tweezers" and tiny probes, are helping propel a remarkable new science and technology of matter at the nano scale. (The prefix nano- means a billionth of, or 10^{-9}; a row of 10 hydrogen atoms is about one nanometer wide. For more about nanoscale science, please see page 24.)

a) From cryoelectron microscopy and image reconstruction, the most detailed view to date (8-angstrom resolution) of a microtubule, a weave of proteins in a cell's skeleton.
b) "Baby picture of the universe," made from microwave after-glow of the Big Bang – light that has traveled for 13 billion years.

c) To exploit nuclear fusion as a renewable energy source will require new knowledge about the properties of superheated gases, or plasmas. Scientists with the Center for Extended Magnetohydrodynamic Modeling, a DOE/SC collaboration of Federal labs and universities, are developing techniques to visualize plasma behaviors, such as the stable toroidal state shown.

d) Computationally rendered image of specialized cardiac cells called myocytes that make hearts beat; cells are stained to show mitochondria (red), DNA (blue), and F-actin (green). e) Unidentified diatom sitting on a cockleburr seed. Details on page 52.
f) 3-D data, like terrain, have a topology; image of fuel injected into chamber, from automated techniques for data analysis and transfer to show topologically equivalent regions (varying by color, opacity).
g), h) Virtual reality hardware and software technologies enable scientists to physically manipulate data-based 3-D structures. Details on page 52.
i) Water molecule – vector-field techniques show electronic charge density. Details on page 52.

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PHONE HOME: Communications with NASA's twin Mars Exploration Rovers, Spirit and Opportunity (launched June 10 and July 7, 2003, on their six-month, 34-million-mile journey) may benefit from the fact that Mars will be closer to Earth than at any time in the last 73,000 years. One-way transmission time will be 11 minutes, compared with 19 minutes during the 1976 Viking mission. In the agency's most elaborate deployment of IT capabilities to date, scientists and engineers are running the Mars mission using advanced hybrid networks, a new class of interactive collaborative computing platform, and custom software tools for real-time distributed mission planning, rover remote control, data analysis, and imaging – all integrated to enable large-scale collaborative management of the intricate enterprise. The 400-lb. rovers are equipped with camera, microscopic imager, spectrometers, and robotic drilling arm to look for signs of life amid the red rocks.

At the intersection of diagnostic devices, computer science and engineering, and medical practice, visualization technologies are also providing powerful new clinical tools. Physicians and surgeons can see exactly what form an individual patient's condition – such as broken bones, a tumor, or a vascular obstruction – takes inside the body and work with that information visually in considering approaches for treatment. A physician can custom-engineer prostheses, such as joint replacements, using computer modeling and then evaluate the designs in the context of a patient's particular anatomy.

Harvard University researchers supported by NIH and NSF are leading developers of such next-generation tools. Starting with the megabytes of data produced by CAT and MRI cross-sectional scanning, traditionally rendered as long sequences of 2-D grayscale images, the researchers computationally segment data representing the key anatomical features under diagnosis. Advanced visualization techniques translate the data into high-fidelity, 3-D color models of the features. These images from an individual patient can be layered with contextual information, such as the surrounding anatomical environment, the shape and position of the feature relative to statistical averages, and possible surgical routes. In neuroanatomy, one focus of the project, the imaging methods are especially useful in illuminating 3-D structural relationships not captured in a diagnostic scan. Brain surgeons are using the tools both in pre-planning and as guides in the operating room.

Long-distance investigation

Across the fabric of high-end connectivity woven of advanced networking and grid technologies for resource-sharing, NITRD-funded research is now linking researchers and students to the Nation's most advanced instruments for scientific and medical research and providing the computational and storage resources they need to work online. The Alpha Telescience Project, a collaboration of NSF's National Partnership for Advanced Computational Infrastructure (NPACI) and the NIH-sponsored National Center for Microscopy and Imaging Research, puts distant users at the controls of the center's high-voltage transmission electron microscope, with real-time streaming video to the desktop. An accompanying application allows the user to create a quick low-resolution version of any microscopic feature to see if it is of interest before deciding to acquire the full tomographic data. Telescience Project developers are prototyping an additional grid-enabled capability that will allow microscope users to generate 3-D tomographic images immediately via distributed parallel processing.

Making another kind of specialized resource – human expertise – more widely accessible is the focus of NIH efforts employing networking and telepresence capabilities for advanced medical training. Expertise in clinical medicine is more than intellectual; it also derives from "hands-on" experience in examining patients and performing surgical procedures. Researchers at Stanford University are using NITRD-developed "haptic" technologies – software and hardware tools for simulating the sense of touch – to help students experience surgical techniques over the Internet. A master surgeon at one location "traces" a surgical procedure with a haptic instrument connected to a computer, which translates the actions into software. A student at a remote computer receives a copy over the Net and, holding the haptic device, lets the software guide his or her hand several times. After a few practice tries, students rehearse the technique independently. These interactions can be stored and reused.

In addition to connecting users to unique resources, NITRD efforts connect distributed data-gathering instruments via networks delivering types and quantities of real-time empirical data that a lone scientist could not hope to amass in a lifetime. Remote-sensing, imaging, and wireless networking technologies developed by DARPA, DOE/SC, NASA, NIST, NOAA, and NSF support real-time monitoring systems for many domains of the national interest, such as air and water quality, rain acidity, drought and fire conditions, seismic and volcanic activity, and melting of the polar icecaps.

As a key weather-monitoring agency relied upon around the world, NOAA expects to collect an average of 2.5 terabytes of data daily from a global network of satellite-based sensors, 156 Doppler radars (a technology developed jointly by NOAA and NSF researchers), ocean vessels and buoys, radiosondes and surface observation stations, and makes much of the information publicly available online. NOAA's real-time observations are the mainstays of major U.S. sectors, including armed services' and civilian weather forecasting, emergency preparedness, aviation and ground transport, agriculture and fisheries, and recreation and tourism.