Energy & Technology Review

- *The Harold Brown View: LLNL Then and Now*
- *Visualizing Dynamic Systems in Three Dimensions*

University of California • Lawrence Livermore National Laboratory

About the Cover

With increases in speed and memory size, today's supercomputers are accommodating an ever-increasing number of large and complex problems. The amount of data generated by these problems defies the standard methods of analysis because it is simply too massive—there is more than we can analyze within a reasonable amount of time. One solution is to convert this information to a visual form and display it on a screen for analysis. Nelson Max and Roger Crawfis, computer scientists at LLNL, have done just that—they have developed algorithms for translating numerical data into three-dimensional animation. Here they have been used to visualize fluid flow through aerogel fragments (background square) and turbulent flow through smoke (uniform rectangular segments). For more information about these algorithms, see the article starting on p. 9.

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About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, we have added other major programs, including laser fusion and laser isotope separation, biomedical and environmental science, strategic defense, and applied energy technology. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computer science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other Federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. Please address any correspondence concerning *Energy and Technology Review* to Mail Stop L-3, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551.

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The Harold Brown View: LLNL Then and Now

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Harold Brown, the Laboratory's third Director and now a Counselor at the Center for Strategic and International Studies, Washington, D.C., reminisces about his years at Livermore and comments about the Laboratory's role in the future.

Visualizing Dynamic Systems in Three Dimensions

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Researchers can use our interactive algorithms to translate massive quantities of numerical data into visual form and can assign the visual markers of their choice to represent three-dimensional phenomena in a two-dimensional setting, such as a monitor screen. We have done major work in the visualization of climate modeling, but our algorithms can be used for visualizing virtually any phenomena.

Abstracts

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Harold Brown: LLNL Then and Now

As part of LLNL's 40th anniversary observances held during 1992, the six former Directors were asked to participate in a lecture series. Each of these men contributed in important ways to making the Laboratory what it is today. Each was asked to comment on their years at Livermore, their view of the changing world, and their vision of the Laboratory's role in the future. This article is based on Dr. Brown's talk of August 21, 1992.

I think it's appropriate, after 40 years, for former Directors and others to come back to the Laboratory, reminisce a bit, assess the past, and think a little about the future. For each of these elements, I believe it's necessary to understand the various contexts that influenced the Lab's history and, in turn, the ways in which the Laboratory affected its external environment. First, some reminiscing.

Reminiscences

As you all know, the Lab was created on the site of what had been a World War II naval training station. It was also the site of a large technology project known as the Materials Testing Accelerator. The MTA was designed to produce tritium and plutonium. It probably would have worked, but it turned out to be unnecessary—or at least not the best way of doing the job. [The early

availability and efficient operation of production reactors made the MTA superfluous.—Ed.] There was a lesson there, which we seem to have to learn over and over again, about pushing technologies that are technically feasible but perhaps aren't appropriate, or economically competitive, or somehow fail to meet the needs of their larger environment.

The Livermore laboratory came into being partly through a wish to

provide a competitive prod to an existing institution, the Los Alamos Laboratory, and partly because of different technical and political judgments as to what nuclear weapons technologies were feasible and desirable. The Laboratory was born of the Cold War, which had intensified in the early 1950s. Stalin's blockade of Berlin in 1948, the

outbreak of the Korean war in June of 1950, the detonation of the first Soviet atomic bomb in August of 1949, and President Truman's subsequent decision to proceed with the development of the hydrogen bomb—all of these events contributed to the sense of urgency that surrounded the founding of the Laboratory.

Over the more than 40 years that the Cold War occupied center stage in international relations, the Laboratory posted some major technical achievements. It introduced small, tactical nuclear weapons, from artillery shells to missiles. It was also an innovator in producing lightweight thermonuclear weapons for multistage, solid-fuel ballistic missiles such as the Polaris and later the Minuteman.

The first of these, the small, tactical nukes, turned out to be an excursion that persisted. Their value was to ensure the credibility of a continuous powder train, so to speak, so that any Soviet conventional aggression would have to face the likelihood of escalation to strategic nuclear war. This had a considerable deterrent effect. The second innovation, embodied in the solid-fuel ballistic missile, came to be the key element of our strategic deterrence policy. Deterrence has outlasted the Cold War, though in a modified and less destructive version.

As I suggested earlier, we also followed a number of false trails. One of these was the Plowshare project, which I helped blaze myself. Plowshare—which was intended to demonstrate the application of nuclear explosives for peaceful purposes—proved the economic and technological feasibility of the idea. However, its negative side effects, real or perceived, made it a practical impossibility.

There was another lesson there that I failed to learn, because I went through a similar experience some years later. The issue was how to base the MX ICBM, and ideas that at the time seemed completely sensible and economically and technologically feasible turned out to be unacceptable in terms of public perception.

So I think that although the Laboratory has a distinguished record, it's not by any means a

An informal evening. Shown here are Mark Mills (Deputy Director of the Livermore Laboratory, left) with Harold Brown, Edward Teller, and John Foster, the Laboratory's third, second, and fourth Directors, respectively. Mills was killed in April 1958 in a helicopter crash at Enewetak.

Polaris, a submarine-launched ICBM. Before he became Director, Harold Brown led the Livermore team that designed the warhead for this missile.

perfect record. It is a record of significant and honorable contributions to a process of 40-odd years that, in my judgment, stands out as unusually consistent, persistent, and, in the end, successful American foreign policy. And it succeeded without a major world conflict.

I think that's something to be proud of. But the Lab shouldn't conclude, as it is sometimes tempted to do, that it played the key or even major role. That credit goes to a succession of political leaders extending over eight administrations, and especially to those who initiated the policy of containment: President Truman, Secretary of State George Marshall, Senator Arthur Vandenberg, Secretary of State Dean Acheson, and President Eisenhower, among others.

Those are some of my views about the past. But what about the future? What is the world going to be like

over the next couple of decades? During the past few years, we've seen two revolutionary developments. One is the end of the Cold War and the new kinds of national security problems that change will bring. The other is the globalization of the world economy and its effect on the U.S. economy. I'd like to address the first of these here, although both will have a profound impact on the way the Laboratory does business.

New World, New Problems

I'd like to turn first to the international security environment, since I believe that a large part of the Lab's mission will continue to be its support of the national security goals of the United States. How do you

Brown and Teller at the LARC (Livermore Advanced Research Computer). Brown was Director during the nuclear test moratorium. He was a driving force in expanding the Laboratory's capabilities for simulating nuclear explosions with computers.

Frigate Bird. The Frigate Bird test in 1962 was the only atmospheric nuclear test of an ICBM—the Polaris—from launch to detonation. This record of the event was taken through the periscope of one of the observation submarines.

The Sedan Crater. This landmark of Project Plowshare was created in 1962 to demonstrate the feasibility of using nuclear explosives for excavation. Thousands of tons of earth were displaced to create a crater measuring some 100 m deep and 365 m in diameter.

Harold Brown: A Distinguished Career in National Security Policy

Harold Brown was the Laboratory's third Director (1960–61). He studied physics at Columbia University under Nobel Laureate I. I. Rabi, earning his Ph.D. in 1949. In 1950, Brown took a research position at the University of California Radiation Laboratory in Berkeley under E. O. Lawrence; two years later he was one of the founders of the newly established Livermore Laboratory.

At Livermore, Brown worked on the Polaris warhead and on Project Plowshare, a program designed to apply nuclear explosives to peaceful uses (such as excavating harbors). While at Livermore, he also served on the Polaris Steering Committee, the Air Force Scientific Advisory Board, and the President's Science Advisory Committee. He was a scientific advisor to the U.S. delegation to the Geneva Conference on Nuclear Weapons Test Detection (1958) and to the Geneva Conference for the Discontinuance of Nuclear Tests (1958–59).

Brown succeeded Edward Teller as Director of the Livermore Laboratory in July 1960. His tenure as Director was particularly challenging as during these years there was a moratorium on nuclear testing. Brown was a driving force in expanding the Laboratory's capabilities for simulating nuclear explosions with computers.

In March 1961, Brown accepted President Kennedy's invitation to become Director of Research and Engineering in the Department of Defense, succeeding Herbert York (the Laboratory's first Director). In 1965, Brown was appointed by President Johnson as Secretary of the Air Force.

Brown left Washington in February 1969 to become President of the California Institute of Technology. While at Cal Tech, his public policy efforts were largely devoted to promoting of arms control. In June 1969, President Nixon named Brown to a five-man commission to prepare for the Strategic Arms Limitation Talks (SALT) with the Soviet Union; Brown was a member of the U.S. negotiating team for both SALT I and SALT II.

In January 1977, President Carter selected Brown for Secretary of Defense. In this position, Brown announced the cancellation of the B-1 bomber program, supporting instead revamped B-52s armed with cruise missiles. (The Persian Gulf War clearly proved his contention as to the military effectiveness of such "smart" weapons.)

After leaving his post as Secretary of Defense in January 1981, Brown joined the Foreign Policy Institute of The Johns Hopkins University Paul H. Nitze School of Advanced International Studies as a Distinguished Visiting Professor. In July 1984, he was appointed Chairman of the Institute. In July 1992, he joined the Center for Strategic and International Studies in Washington, D.C., as Counselor. He continues a variety of activities in the private sector, including corporate directorships and consulting, and is a partner in a New York-based venture banking partnership.

define U.S. security? I define it as protecting America against external threats to its physical survival, to its democratic form of government as embodied in the Constitution, or to the well-being of the people of the United States.

By that definition, issues of international trade and market access have a strong bearing on national security, since it's clear that they have an impact on the living standards of the American people. In a general and profound sense, our ability to deal with external threats depends on our economic strength and our domestic cohesion. But as you get more specific, you begin to cross a blurred line. Access to health care, slow productivity growth, racial conflict, widespread violence in our cities, injustice, and street crime are very high on our list of concerns and are real threats to the American public. But by my definition, they're not part of national security because they are not the effects of forces outside the United States. That's the distinction I make.

The collapse of the Soviet empire, the demise of the Soviet Union itself, and the subsequent end of the Cold War obviously color what must be a new approach to U.S. security policy. But while these events argue that we should shift some of the military and political burden to our allies and to international bodies, it doesn't mean that military threats have disappeared. Specifically, the most important goal of U.S. security policy is still to ensure that we're not annihilated by nuclear weapons.

At present, we do not have any acute differences of the sort that could lead to war with Russia, with any of the other former Soviet republics (some of which still have nuclear weapons), or with China. Still, those weapons are capable of destroying the United States. This

means, I think, that we must retain a deterrent force, if not at the same level of readiness. Nor does this raise the prospect of a new arms race. As the reduction of political tensions demonstrates, it was political differences that drove the arms race rather than the reverse. And it wasn't the arms pacts, valuable as they were, that led to the end of the Cold War; the easing of the Cold War made more sweeping arms reductions feasible, and those, in turn, helped wind down the adversarial postures.

A credible deterrent should be feasible at a substantially lower level of nuclear weaponry. Whether this means 5000 warheads or 3000 or 10,000 is an issue I won't go into now, but it will be much lower than it is now. Whether active defense can, under these new political circumstances, prevent catastrophic destruction from a massive nuclear attack, unlikely as that scenario might seem, is another question. My answer continues to be "no." An arguable case (but one that doesn't convince me yet) can be made for a thin, ground-based defense against a light, accidental nuclear attack. However, I do believe there is a legitimate role for a defense against short-range ballistic missiles—including, and especially, nonnuclear missiles.

There is now no credible conventional arms threat of any magnitude to the United States. But there do remain geographic areas that are important to us outside our own borders. In first place is Western Europe, for obvious reasons. Since World War II, Japan—and by extension—South Korea have assumed an analogous but second place. It is reasonable to add to these the Persian Gulf region because of its energy resources, Israel because of the special responsibility the United States feels toward it, and finally, in

our own back yard, the Caribbean region, Mexico to its border with Guatemala, and perhaps (depending on whom you talk to) Panama and the rest of Central America.

Beyond these, I would say that our geographic security interests are derivative. As a country, we think it's important that democracy be encouraged everywhere in the world and that all nations regard their neighbors peacefully. But in fact, beyond the geographical regions I've described, the United States faces

few threats to its security almost no matter what happens outside of those regions. There are some generic exceptions to this principle.

Proliferation of nuclear weapons or chemical or biological weapons to outlaw states can threaten U.S. interests significantly. In addition, there may be global ecological threats; these are often overdrawn but they can be significant.

The United States can and should respond to threats to peace by working through collective bodies

Waiting for President Kennedy to arrive at UC Berkeley (1962). Shown here from left to right are Edward Teller (past Director of the Livermore Laboratory), Robert McNamara (Secretary of Defense), and Harold Brown.

such as the United Nations. In doing so, we will be giving up some freedom of action but the result may seem worth that price. However, there will also be cases where American interests will be directly involved. So it's important that we be prepared to act unilaterally if necessary.

Solutions in Search of Problems

Let me turn now to the future of the Laboratory. As I've suggested, national security will continue to play an important role in the Lab's mission. Assuming that events in Russia don't take a turn for the worse, I think we're moving now toward minimal deterrence. Nuclear weapons are losing their function of extended deterrence, a function that they retained for a longer period than was credible on the basis of analysis

alone. They have also lost their war-fighting function, which I don't think they ever really had.

During this transitional period, we're not likely to demand higher yield-to-weight ratios or special effects from our nuclear weapons. But the need for enhanced safety and stability, as well as the need for compatibility with delivery systems different from those that the warheads were designed for, are likely to continue. And, of course, we will have to retain the capability to design new weapons should the need ever arise. There is thus still a significant but shrinking role for the nuclear weapons program.

I believe that the inertial confinement fusion program may well have a substantial future. This includes not only the simulation of weapons designs and weapons effects but perhaps—in some quite distant

future—as a generator of electrical power. Because of budget limitations, it isn't as far advanced as magnetic confinement fusion. That makes it seem more promising. But then again, maybe you just haven't discovered all the problems yet.

Another area for which there's going to be considerable demand is computer software, especially for massively parallel processing, for large communication networks, for simulation and modeling such phenomena as deformation of structures, hydrodynamics, aerodynamics, earthquakes, climate and weather, and so on. The Laboratory has developed considerable skills in these kinds of applications, and is doing interesting and important work in many of them. Whether the Lab is able to play a leading role in the world of distributed computing using open

President Kennedy visits UC Berkeley (1962). Shown here from left to right are Norris Bradbury (Director of the Los Alamos Laboratory), John Foster (Director of the Livermore Laboratory), Edwin McMillan (head of the Lawrence Radiation Laboratory at Berkeley), Glenn Seaborg (head of the Atomic Energy Commission), President John F. Kennedy, Edward Teller (past Director of the Livermore Laboratory), Robert McNamara (Secretary of Defense), and Harold Brown.

systems, which may be the future direction is more problematic.

Working with the Private Sector

I could mention other opportunities for the Laboratory to apply its skills, such as energy and environmental problems and high-power lasers for nonweapons applications. In all of these, and more, the Lab's multidisciplinary approach, its collection of very smart people, and its five-billion-dollar investment in physical plant are not easily matched outside the nuclear-weapons community. These are very substantial assets. However, they're not enough.

In exploiting these assets, whether in the private or public sector, the market-pull approach is vital. It's not enough to say, "We're bright, we've got good ideas, we're highly educated, we have a very expensive plant with all sorts of technological capabilities. Come see what we've got, and I'm sure you'll want to buy." That won't work. I think the Lab understands that. In recent years, the Lab has done a lot to give itself market connections.

The private-sector market is much tougher than the national-security market and, indeed, tougher than the government's nondefense market. There are several reasons for this. First, the nuclear weapons business aside, you don't have a monopoly. There are many more competitors out there. And the customers are much more diverse. If you think that dealing with the Department of Energy and the Department of Defense is a nuisance, try dealing with the VCR purchaser. The private-sector market is also time-critical. You may have a better product, but if you're a few months late, it may well fail because a competitor has

established a marketing infrastructure and a customer mind-set you won't be able to overcome.

What this means is that you need to be partnered closely either with those who know the marketplace, whether [they be] original equipment manufacturers or big companies that are used to selling in the private sector, or with private consortia. You can try to deal with government customers—the infrastructure customers—outside the national security sector. Often that means local governments, which have their own problems that are different from the federal government's but no easier to deal with, and sometimes harder.

In the private sector, costs count. They count less in government infrastructure markets for the same reasons that they fail to count, or don't count enough, in the national security sector. One horrendous problem in mixing national security and private sector programs is in the overhead costs incurred by the enormous volume of paperwork, multiple reviews, and so on that characterize government work. While supporting this burden, you aren't going to do very well in the private marketplace because your competitors aren't equally handicapped. That's why a great many aerospace companies have fallen on their faces in the civilian markets while trying to produce buses or whatever.

Dealing successfully with all these challenges is going to take a change in culture. That won't come easily, and it's probably going to require a generational change as well. The people who performed so successfully during the past 40 years are unlikely to be the ones who are going to handle the next couple of decades, even if they live that long.

Questions and Challenges

I leave you with some questions. Can the country solve or at least manage its security problems over the coming decades? They seem to me to be far less dangerous than those of the past 40 years but in many ways more complicated. Thus, while the problems may not be any easier to cope with, the consequences of failure may not be as severe. Can the country manage its domestic and economic problems? Can the Lab solve its (much smaller) problems of adjusting to these changes?

Only time will tell. The country's economic and social problems aren't going to be solved easily. Although they may be more challenging than those of the past 40 years, they're certainly not harder than those of the 1930s. Thus I would say there are reasons to be optimistic, both for the country and for the Laboratory. Frustrating as it may be at times, the democratic process still corrects itself in ways that other systems do not. We did successfully carry out the policy of containment over the past 40 years, until the object of containment was transformed. During the next 20-odd years, technology-driven growth can provide a significant resource to meet our domestic problems and to manage a new security environment.

I think the Laboratory can contribute to achieving both of these ends. You have an abundance of talent, and I see encouraging evidence of the adaptability and vigor you will need to play as significant and honorable a role in this process as you did over the past 40 years.

For further information contact Harold Brown at the Center for Strategic and International Studies, Washington, D.C. (202) 887-0200.

Visualizing Dynamic Systems in Three Dimensions

How can we display large amounts of data from a three-dimensional system on a two-dimensional screen without sacrificing accuracy and richness? Answer: convert the data to a visual form using our new algorithms. These algorithms, although initially developed as visualization tools for climate research, can be applied to any field of scientific investigation that generates or collects three-dimensional data.

“EVERYBODY talks about the weather, but nobody does anything about it.” When Mark Twain wrote those words in 1897, the joke was that no one *could* do anything about it. Nor can we now. However, there may be an ironic twist to the joke: it may be that, even in 1897, human activities had already begun to have subtle but cumulative effects on *climate*. The prospect of a warming of the Earth’s atmosphere has been a matter of lively concern and some controversy in recent years.

We know that the burning of fossil fuels worldwide has been putting pollutants into the air at a steadily increasing rate for the last 200-odd years, since the beginnings of the industrial revolution. But are these accumulated airborne products creating global warming?

The potential climate changes are being driven by changes to the composition of the Earth’s atmosphere. Emissions from the burning of coal, oil, gas, and the forests have increased the atmospheric concentration of carbon

dioxide by 25% since pre-industrial times. The concentration of methane has more than doubled in the same time, and the atmospheric concentrations of chlorofluorocarbons have increased rapidly over the course of this century. There is general agreement that the climate will change in the next century as a result of these increases, but there is not yet agreement on the extent or rate of change or on how regional patterns of temperature and precipitation may change. Because

the climate system is so extremely large and complex, researchers have had to construct theoretical models of all the components of the system—the atmosphere, oceans, and land masses—and solve the resulting equations on the fastest supercomputers.

Among these models is a category called general circulation models (GCMs), which divide the global atmosphere into hundreds of thousands of discrete cells and use the dynamical equations of motion, energy, and mass to predict the changes in winds, pressure, and humidity. The nearly twenty GCMs in use worldwide are similarly designed, but all show a variety of systematic errors. As a result, when the same change is made to an atmospheric factor in all these models, no two models produce the same changes in effects. LLNL's Program for Climate Model Diagnosis and Intercomparison (sponsored by the Department of Energy's Atmospheric and Climate Research Division) is comparing these climate models to identify the sources of disagreement in their simulations.¹

For global warming and related environmental problems such as ozone destruction and air pollution, we can investigate the causes and solutions by simulating the dynamics of the Earth's atmosphere. Computer simulations dealing with the atmosphere—or with the ocean, hydrodynamics, electromagnetics, structural response, and environmental clean up—generate very large and complex data sets consisting of scalar variables and vector quantities. The scalars are those quantities that have magnitude

but no direction; examples are temperature, humidity, and percent of cloudiness. Vector quantities, such as wind velocity, have both magnitude and direction.

Scientific Visualization

In recent years, as computers have grown in speed and memory size, they have been applied to ever larger, more complex problems. The tens of gigabytes of data being generated by today's supercomputers on such problems defy the standard methods of analysis—there is simply more information than a researcher or team of researchers can process and analyze in a reasonable amount of time. Scientific visualization—the conversion of quantitative data into visual representations—has therefore become a standard tool.

Visualization tools are necessary to the understanding of the scalar and vector outputs of global climate simulations. Algorithms convert the masses of raw data (whether collected at sensing stations or generated by computer simulation) into visual formats that the users assign and with which they can interact. We have developed several techniques for visualizing these climate variables, particularly clouds and wind velocities. All involve algorithms—well-defined calculational procedures—for converting numerical data into optical properties, such as color and opacity. These algorithms represent advances in the state of the art, providing new visual effects, particularly for overall views of large data sets.

It should be noted that our work in visualization is not directly related to the design and performance of climate models, GCMs or otherwise.

Our work is focused solely on the means of translating numbers into visual forms in order to make the information embedded in the numbers visible for interpretation and analysis. In this article, we show applications to other areas of research besides climate modeling.

Using our techniques, we produced a high-definition television (HDTV) animation showing the global cloud motion during ten simulated days in January.² Several of the illustrations in this article are frames from this demonstration film. The climate simulation was run on a Cray-2 computer at the National Energy Research Supercomputer Center at LLNL. The computational grid was defined by 320 evenly spaced longitudes, 160 unevenly spaced latitudes, and 19 unevenly spaced vertical levels. This grid has nearly a million data points. Among the variables that can be output are temperature, pressure, humidity, wind velocity, short-wave and long-wave radiation, and cloud density. Since we cannot describe these algorithms in any detail without resorting to mathematics, we will briefly sketch what several of our algorithms do. Readers wanting more information may consult the Notes and References at the end of the article.³

Realistic Cloud Cover

Clouds have a significant influence on global temperatures. They reflect short-wave radiation from the sun, and they also absorb and reflect the longer-wave radiation reemitted by the Earth. It is not certain whether these effects balance each other or, if they do not, which of the effects is larger. Clouds are the least understood component of climate

models. It is not even known whether global warming will cause an increase in cloudiness. If climate changes, will cloud response magnify the change or reduce its severity? The influence of clouds is thus an active research problem.

Rendering Cloudiness

We have devised techniques for visually rendering cloudiness that exceeds a threshold percentage chosen by the user. Figure 1 shows the contour surfaces of 15% cloud cover as viewed from outer space, with a large magnification in the altitude direction.

We can also draw partially transparent, hazy clouds using volume rendering. Volume rendering is any method that allows the user to render, in a two-dimensional medium such as a TV monitor screen, a visual representation of what is going on within a volume cell—a defined volume of three-dimensional space. (Each segment of our $320 \times 160 \times 19$ grid of the atmosphere, mentioned earlier, is a volume cell.) Since the Earth presents a smooth surface only over its bodies of water, the GCMs and our volume-rendering techniques have to account for the rises and falls of the Earth's terrain. Figure 2 shows a side view of the atmosphere projected over a flat map of the world.

Texturing Clouds

Since our grid cells are 1.125 deg on a side, each cell encompasses some $10,000 \text{ km}^2$ at the equator. When this area is reduced for presentation on a monitor or HDTV screen, we cannot possibly represent individual clouds. Instead, the clouds represent the percentage of cloud cover at a particular altitude within that cell. This makes the contour surfaces of Figure 1 look too smooth.

We created an algorithm that adds texture to clouds, controlling cloud transparency and allowing small breaks in cloud formations (see Figure 3). Thus, although the clouds shown actually represent a quantity (the percentage of cloudiness), they have the look of actual cloud masses seen from a distance.

The texture adds an amount of realism to the static image of the

clouds. Since the clouds move as the simulation progresses in time, we must also move the texture coherently with the moving cloud contours. We used the wind velocity data at each time point in the simulation to calculate how the texture should move. Figure 3 shows four successive frames in our HDTV animation. The moving texture indicates wind velocity.

Figure 1. Simulated cloudiness, with contours of 15% cloud cover.

Figure 2. Side view of the atmosphere projected over a flat map of the world, with outgoing long-wave radiation (heat) color-coded on a plane at the top of the atmosphere.

Figure 3. The same volume-rendered cloud contours as in Figure 1 with a transparency texture added for greater realism. These are four successive frames from our HDTV animation.

Visualizing Wind Patterns

Time-lapse satellite images of weather systems in motion are a commonplace of TV weather reporting. Thus we are used to seeing large air masses in motion, made visible by their cargo of cloud mass. However, anyone who has flown into the violent updrafts and downdrafts of clear-air turbulence knows that a lot can be happening in the atmosphere that is not visible to the naked eye. Often the jet stream, the fast-moving high-altitude current, figures prominently in TV weather reporting, but it can be made visible only by some wholly artificial-looking, snake-like animation. We too need a way to make wind visible in the absence of clouds or other visible markers (such as smoke), but the technique must be subtle enough to show fluid motion over time and allow high resolution of detail.

Current tools for displaying directional flow fields, like wind, present too much visual clutter or lack visual coherence. Our approach to representing three-dimensional flow fields solves these problems. Our tool generates high-frequency patterns resembling an artist's brush strokes that are suggestive of thin, transparent wisps of hair floating on the wind. We build up layers of these wisps to construct the final image—either a single still or a frame from an animated film (see Figure 4).

In an animated film, as the directional flow propagates in time, these wisps do not move as the clouds and texture do. Instead they are continuously replaced, always with a slight change in direction or location to suggest motion from

frame to frame. The speed or force of the wind is indicated by the density of the pattern rather than by the length of the individual wisps. The net result is a fairly coherent representation of the flow in both a static image and a time sequence.

The standard perspective and lighting cues that give an object its three-dimensional appearance do not work well on these wisps, so we use color mapping to indicate their altitude. The surface winds in Figure 4 are blue to cyan, the jet stream winds are green to yellow, and the upper atmospheric winds are red to magenta.

Interactive Visualization Techniques

The algorithms described so far are strictly software creations. However, current high-end graphical workstations have special hardware

to do high-speed image rendering, including texture mapping. We have adapted our algorithms to exploit this hardware, increasing the speed and efficiency of their performance to the point where interactive manipulation is possible. For example, the tornado in Figure 5 can be viewed interactively in three dimensions, and the texture can be animated to show movement of the flow field.

Although the examples so far have dwelt on atmospheric and climate models, our algorithms can be applied to virtually any problem that admits of visual representation and that involves scalars and vectors—and few phenomena fall totally outside these criteria. For example, LLNL researchers have developed a variety of aerogels—solid foams that are of such low density that they are almost entirely empty space. Aerogels have outstanding thermal and acoustical

insulating properties, and other remarkable properties as well—one silica aerogel with three times the density of air has the strength to support 1600 times its weight. Aerogels hold great promise for many applications of tremendous value to today's commercial environment.⁴

The development of aerogels at LLNL involved both experiment and sophisticated computer simulations to determine their structural features and their properties—for example, how such extremely low-density materials can perform such feats of insulation. Our techniques of visual representation are flexible, allowing researchers to choose the visual means that are most suited to their needs and make the data intelligible on the monitor screen.

Figure 6 is such an example. In this simulation of air flow through an aerogel, the odd opaque shapes represent the aerogel material, but the patterns of airflow have been handled

Figure 4. Wind velocities color-coded by altitude: blue to cyan for surface winds, green to yellow for jet stream winds, red to magenta for upper atmospheric winds. The density of the wisps indicates wind speed.

Figure 5. A computer-generated tornado. This simulation can be viewed interactively in three dimensions and the texture can be animated to show movement of the winds.

quite differently from the wind patterns in the climate model. Here, the different colors represent different magnitudes of velocity, and tiny animated strokes indicate the direction of the air flow through the aerogel.

Although the use of tiny strokes for vector direction is not new in itself, we were able to integrate the strokes with volume-rendering techniques. This efficient merger of volume rendering and vector plots

encodes subtle clues about the flow patterns of winds within the clouds, as Figure 7 shows.

Interactive Smoke Generator

An aerogel is also simulated in Figure 8. Here we have used a different device for representing flow—an interactive smoke generator that simulates the release of smoke into the fluid flow. This sort of device is useful for focusing on specific regions within a problem domain in order to gain a more thorough understanding of the simulation. It is a volumetric version of the streamline (a one-dimensional stringlike line representing the path of a particle in a flow).

The smoke generator is faster than volume rendering (as seen in Figure 2, for example) since only the regions of interest, the smoke-filled regions, are drawn. The user can interactively place the smoke generator in the flow field and view the results. Figure 9 shows our smoke generator placed within the winds generated from the global climate model.

Our smoke generator supplies several options to help probe a flow field. The user controls the amount of smoke generated by scaling the size of the probing device, controls the accuracy of the advection, and controls the thickness and color of the smoke. Our smoke generator allows the smoke volume to expand and distort as the flow spreads it out.

With real smoke, stagnant areas in the flow field are very thick and opaque, and areas with rapid flows spread the smoke out, making it more translucent. An option in our smoke generator allows us to show this varying concentration of the smoke. Figure 10 shows a simulated turbulent flow within which both the

Figure 6. Fluid flow through an aerogel (the odd, yellow-colored shapes are the aerogel fragments). The cloudy areas of color represent magnitudes of velocity; when seen in animation, the strokes show direction.

Figure 7. View within the clouds over North America. When seen in animation, tiny colored strokes propagate forward, providing a view of the winds within the cloud fields.

dispersion and compression options of the smoke generator have been activated.

Summary

Supercomputers and parallel computers have enabled researchers to gather ever more massive quantities of data and to create high-resolution simulations. The processing of such huge quantities of information has become humanly impossible without the intervention of scientific visualization—computer methods of converting data into visual formats that allow the information to be grasped and analyzed.

We have created algorithms that allow three-dimensional data, both scalar and vector, to be represented visually. The algorithms cover a wide range of techniques, from those for showing the cloud cover over the globe or a portion of it, to those for representing global views of vector fields (such as global wind currents), to the interactive smoke generator for studying flow patterns in specific areas. Although much of our attention in developing these algorithms has been directed to atmospheric research, these algorithms can be applied to virtually any realm of scientific investigation, right down to the simulation of atomic and subatomic events.

Key Words: aerogels; global climate modeling; scientific visualization—interactive; scalar data; three-dimensional; vector data; volume rendering.

Notes and References

1. For a thorough investigation of global climate models, see the May–June 1990 issue of *Energy and Technology Review* (UCRL-52000-90-5/6).

Figure 8. Smoke (from the magenta rectangle) being released into an aerogel. When seen in animation, the constriction of the smoke, from a plump plume to a stringy one, suggests the effectiveness of aerogels as insulators.

Figure 9. Here, the smoke generator is placed within the winds generated from the global climate data set (Figure 2); the smoke plume shows the winds that stretch from central Africa to northern Australia.

Figure 10. Simulated turbulent flow using the smoke generator. The relative densities within the smoke plume give information about localized conditions within the flow, with the dense areas being relatively stagnant and thin areas having swifter flow.

- on research in the atmospheric sciences at LLNL, and particularly the article starting on p. 56.
2. In 1993, the film by N. Max and R. Crawfis, "Global Climate Visualization," received a first-place award from the NICOGRAPH Association.
 3. For more information on the algorithms, see the following publications:
 - R. Crawfis and N. Max, "Direct Volume Visualization of Three-Dimensional Vector Fields," *Proc. 1992 Workshop on Volume Visualization* (October 1992), ACM SIGGRAPH, New York, pp. 55-60.
 - R. Crawfis and N. Max, "Texture Splats for 3D Vector and Scalar Field Visualization," *Proc. Visualization '93* (October 1993), IEEE, Los Alamitos, CA, pp. 261-266.
 - N. Max, P. Hanrahan, and R. Crawfis, "Area and Volume Coherence for Efficient Visualization of 3D Scalar Functions," *Computer Graphics* **24** (5), 27-33 (November 1990), special issue on San Diego Workshop on Volume Visualization.
 - N. Max, R. Crawfis, and D. Williams, "Visualizing Wind Velocities by Advecting Cloud Textures," *Proc. Visualization '92* (October 1992), IEEE, Los Alamitos, CA, pp. 179-184.
 - N. Max, B. Becker, R. Crawfis, and D. Williams, "Volume and Vector Field Visualization for Climate Modelling," *IEEE Computer Graphics and Applications* (July 1993), IEEE, Los Alamitos, CA, pp. 34-40.
 - N. Max, R. Crawfis, and B. Becker, "New Techniques in 3D Scalar and Vector Field Visualization," in *Computer Graphics and Applications, Proc. Pacific Graphics '93*, S. Y. Shin and T. L. Kunii, Eds. (World Scientific, New Jersey, 1993), pp. 301-315.
 - N. Max, B. Becker, and R. Crawfis, "Flow Volumes for Interactive Vector Field Visualization," *Proc. Visualization '93* (October 1993), IEEE, Los Alamitos, CA, pp. 19-24.
 4. The Laboratory's research and development of aerogels is described in the article starting on p. 20 of the January 1991 issue of *Energy and Technology Review* (UCRL-52000-91-1).
 5. We are indebted to the many people who provided the data used in the visualization in this paper. In particular, Tony Ladd and Elaine Chandler provided the aerogel data, and the climate data are courtesy of Jerry Potter, the Program for Climate Model Diagnosis and Intercomparison at LLNL, and the European Centre for Medium-Range Weather Forecasts.
 6. We are also indebted to the Laboratory Directed Research and Development (LDRD) Office, whose gracious funding has made this work possible.

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Abstracts

The Harold Brown View: LLNL Then and Now

Harold Brown was the Laboratory's third Director, serving from 1960 to 1961. He joined the Livermore Laboratory in 1952. At Livermore, Brown worked on the Polaris warhead and on Project Plowshare, a program designed to apply nuclear explosives to peaceful uses (such as excavating harbors). Brown succeeded Edward Teller as Director of the Livermore Laboratory in July 1960. His tenure as Director was particularly challenging as these were the years of the moratorium on nuclear testing. He was a driving force in expanding the Laboratory's capabilities for simulating nuclear explosions with computers.

As part of LLNL's 40th anniversary observances, Brown was invited to lecture on his views of the changing world and the role of the Laboratory. He reminisced about events that occurred in the Laboratory's early years, with an eye to finding lessons for the future. In particular, he cited Project Plowshare and the MX ICBM as examples of projects that were technologically and economically feasible but unacceptable in terms of public perception. Brown also discussed the international security environment and the Laboratory's role in support of the national security goals of the United States. He defined U.S. security as protecting America against external threats to its physical survival, to its democratic form of government, or to the well-being of the people of the United States. By this definition, issues of international trade and market access have a strong bearing on national security. Thus the Laboratory can find much important and interesting work to do under the heading of national security and economic competitiveness. Brown also pointed out, however, that working effectively with the private sector will take a change in culture since the private-sector market is very different from and more competitive than the nuclear weapons world or the government's nondefense market. He concluded by expressing confidence that the Laboratory, with its abundance of talent, will be able to contribute in important and unique ways to the challenges facing the country now and in the future.

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Visualizing Dynamic Systems in Three Dimensions

Modern computers have enabled researchers to gather ever more massive quantities of data. The processing of such huge quantities of information has become humanly impossible without the intervention of scientific visualization—computer methods of converting data into visual formats that allow the information to be grasped and analyzed. We have created algorithms that allow three-dimensional data, both scalar and vector, to be represented visually. The algorithms cover a wide range of techniques, from techniques for showing the cloud cover over the globe or a portion of it, to techniques for representing global views of vector fields (such as global wind currents), to the interactive smoke generator for studying flow patterns in specific areas. Although much of our attention in developing these algorithms has been directed to atmospheric research, these algorithms can be applied to virtually any realm of scientific investigation, right down to the simulation of atomic and subatomic events.

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