Strategic Research at Los Alamos

Rajan Gupta and David E. Watkins

Los Alamos National Laboratory is a scientific institution whose primary mission is to be a steward of the nation's nuclear deterrent. In a broader context, the Laboratory's mission is to preserve the security and safety of the United States against present and future threats. To anticipate future threats and develop the necessary ideas and technologies to detect, foil, and mitigate possible attacks, we must be working at the cutting edge of research in many branches of engineering and science, and we must simultaneously integrate a wide range of research advances from academia and industry.

The long-term success of any scientific organization is tied to its ability to recruit and retain exceptional people and to foster collaboration and meaningful relationships with the finest institutions worldwide. In addition, at Los Alamos and other mission-oriented laboratories, an environment must be maintained in which the creativity of the staff is readily tapped in order to implement those missions. Sustaining that kind of environment is a formidable task. It has been made more complicated because emerging threats—global terrorism, nuclear proliferation, poverty, disease, diminishing fossil-fuel and water resources, stressed ecosystems—require that the Laboratory respond from a broad base of scientific expertise and develop effective responses in a timely fashion.

Unlike many research environments, ours must balance the freedom to explore new ideas with a strong communal commitment to meeting national security challenges and to making sacrifices when necessary. This balance requires the presence of scientific leaders who can inspire others to contribute innovative ideas and who can lead the integration of those ideas into practical solutions. Not only must we divide our efforts between basic research and applied research and development activities, but we must also recognize and seek out synergistic research opportunities in which progress in one field yields greater understanding in another. Finally, there must be a deep recognition that the evolution of ideas is rarely predictable and that the Lab must position itself to encourage the creation and exploitation of new ideas to meet future challenges.

After World War II, key decision makers recognized the value of providing scientific organizations with the flexibility necessary to pursue innovative ideas. While serving as Army chief of staff, General Eisenhower wrote, "Scientists and industrialists must be given the greatest possible freedom to carry out their research. The fullest utilization by the Army of the civilian resources of the nation cannot be procured by prescribing the military characteristics and requirements of certain types of equipment. Scientists and industrialists are more likely to make new and unsuspected contributions to the development of the Army if detailed directions are held to a minimum . . . ." This kind of thinking is reflected again in the Atomic Energy Act of 1954: "The commission is directed to exercise its powers in such manner as to insure the continued conduct of research and development and training activities in the fields specified . . . ."

Currently, within the Department of Energy (DOE) structure, the Laboratory-Directed Research and Development (LDRD) program provides resources for discretionary research. Although this particular formal structure is young compared with the 60-year history of the Lab, the origins of the program go back to the beginning of the weapons program. Indeed, some have argued that the initial work on spherical implosion represents the first LDRD-like effort at Los Alamos. In late April 1943, Seth Neddermeyer proposed that a three-dimensional implosion would be a potentially more effective means of assembling a supercritical mass than the one-dimensional "gun assembly," which was the baseline design concept. Neddermeyer's concept was initially considered unnecessary and outside the mainstream of work. Although the spontaneous rate of plutonium-239 fission is twice that of uranium-235, the difference did not appear to warrant a different design. Nevertheless, Oppenheimer decided to fund the work on spherical implosion to keep the option open. It was not until the data came in on the reactor-produced plutonium, which contained enough plutonium-240 to significantly increase the spontaneous fission rate, that the work on spherical implosion carried out by Neddermeyer and Kistiakowsky was recognized as essential. Today, the flexibility afforded through the LDRD program continues to provide the nation with science and technology critical to our defense and security.

The synergy between the nuclear weapons program and basic science is exemplified by the work of Nobel Laureate Fred Reines. During the war, Reines worked on many different aspects of nuclear weapons design. After the war, he became an expert on nuclear weapons effects and played a lead role in nuclear weapons testing. Toward 1948, Reines wanted to return to basic science. Carson Mark, his division director actively encouraged this transition and gave Reines the freedom to "sit and think." This he did for almost a year, during which time he decided to search for the elusive neutrino, a neutral particle with little or no mass, whose existence was postulated on the basis of the fundamental principle of energy conservation. If theory was correct, this particle should be produced in copious quantities during a nuclear explosion.

Under the nurturing eye of Carson Mark, Fred pulled together his vast experience with detection of different forms of radiation, his abilities to do big science, and the technical capabilities of Los Alamos to build a detector

Continued on page 204

Resolving the Solar Neutrino Problem

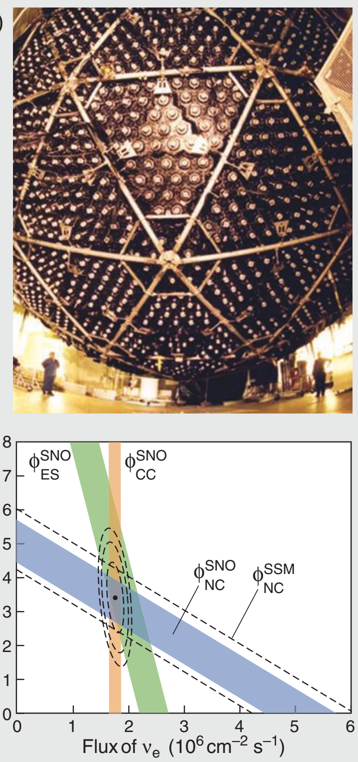
Andrew Hime

Since the seminal discovery of the neutrino by Los Alamos researchers Clyde Cowan and Fred Reines in the late 1950s, there has been a continuous effort by Laboratory scientists to study neutrinos and their interactions. Central to that study is the question of whether the different neutrino flavors—electron, muon, and tau—have mass, a question that has been answered decisively with recent data from the Sudbury Neutrino Observatory (SNO).

SNO was built to resolve the long-standing solar neutrino problem, wherein the measured flux of solar neutrinos reaching Earth is significantly lower than predicted. But all previous experiments had been sensitive to only electron neutrinos. Whereas those are the only neutrinos that can be created by the nuclear fusion reactions powering the Sun, the other flavors can be "produced" if neutrinos have mass. Through the process of flavor mixing, massive electron neutrinos from the Sun can "transform" into muon and tau neutrinos as they travel to Earth. This process would explain why the measured solar electron neutrino flux is lower than predicted by the standard solar model.

(a)

(b)



CC: $\nu_e + d \rightarrow p + p + e^- - 1.44$ MeV
NC: $\nu_x + d \rightarrow p + n + \nu_x - 2.22$ MeV
ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

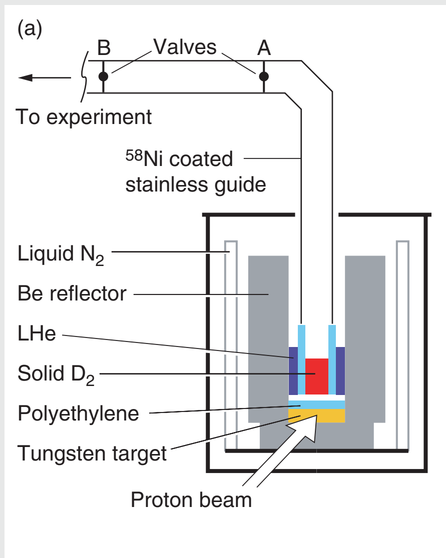
A multinational decade-long effort, SNO was designed to detect all neutrino flavors. Los Alamos was involved in all aspects of the project, including detector construction, commissioning, simulation, and calibration, as well as data analysis and scientific management. The primary detector contains 1000 tonnes of ultrapure heavy water in a large "bottle," shown in (a). The deuterium in the water can interact with high-energy electron neutrinos through charged-current (CC) weak interactions and with all neutrino flavors through neutral-current (NC) weak interactions. All neutrino flavors also undergo elastic scattering (ES) with electrons, but the reaction is sensitive mostly to electron neutrinos. By enabling a direct comparison of the CC, NC, and ES reaction rates, SNO could determine if the neutrinos from the Sun are a mix of electron, muon, and tau neutrinos. As seen in (b), the best fit to the data (dotted circles are confidence limits) indicates that two-thirds of the electron neutrinos born in the Sun transform into muon and/or tau neutrinos. (Φ^{SSM}_{NC} is the NC flux predicted by the standard solar model.) Together with data from other experiments, these results demonstrate that flavor mixing almost certainly resolves the solar neutrino problem and that neutrinos have mass. Moreover, the total flux of neutrinos measured at SNO agrees with predictions and our basic knowledge of how the Sun shines.

A New Source of Ultracold Neutrons

Chen-Yu Liu, Steve K. Lamoreaux, Thomas J. Bowles, and Christopher Morris

A neutron will normally diffuse right through materials such as steel or lead, but if the neutron's energy is exceedingly low, it will instead be reflected by those (or other) materials. We can now produce neutrons with kinetic energies less than about 300 nano–electron volts. When placed in a "bottle" of the right material, these ultracold neutrons (UCNs) become trapped, enabling us to collect them and to make a high-density UCN source.

Such a source can offer orders-of-magnitude improvements to experiments that make precise measurements of neutron properties. For example, Los Alamos is vigorously pursuing an experiment to measure the angular correlation between a neutron's spin and the momentum of the electron that emerges when the neutron decays. The experiment should provide a precise measure of the ratio of the vector and axial-vector coupling constants in the electroweak interaction in the Standard Model, and so can be used to test the unitarity of the CKM matrix (the matrix that rotates the complete set of quark mass states into the complete set of quark weak states). Another experiment aims at improving the limit set on the as-yet-unobserved neutron electric dipole moment (EDM), the existence of which would violate parity and time reversal symmetry. The neutron EDM, therefore, serves as a critical test of fundamental particle theories that are extensions to the Standard Model.



We have recently conducted experiments to understand and characterize the performance of solid deuterium as a so-called superthermal UCN source. As seen in graphic (a), a pulse of high-energy protons from the Los Alamos Neutron Science Center is directed to a tungsten target that sits inside a liquid nitrogen dewar. High-energy spallation neutrons exit the target, lose most of their energy in a layer of polyethylene, and enter the liquid helium dewar that holds the solid deuterium. A neutron can collide with a deuterium molecule and resonantly transfer essentially all of its kinetic energy to the deuterium lattice. By this superthermal process, a relatively large fraction of the incoming neutrons become ultracold. They then diffuse to the UCN bottle region, where the sequenced closing of valves B and A trap them.

We have demonstrated a prototype, solid deuterium source, shown in (b), that produced about 120 UCNs per cubic centimeter inside the bottle region, a much higher value than can be provided by other facilities. A source with potentially six to seven times that UCN density is being engineered for the angular correlation experiment mentioned above. We are also investigating solid oxygen as a candidate for the next generation superthermal UCN source. Our preliminary calculations indicate that this new material might yield a UCN flux output 250 times greater than than that achieved with solid deuterium.

The National High Magnetic Field Laboratory—A User Facility

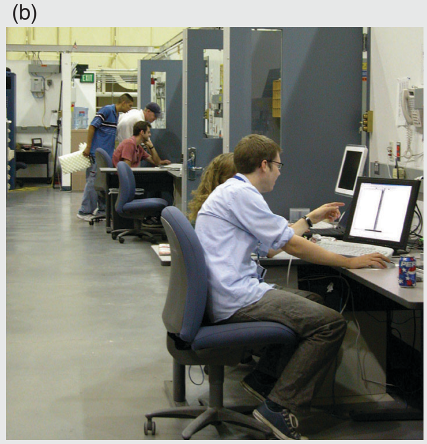
Alex H. Lacerda and Gregory S. Boebinger

The National High Magnetic Field Laboratory (NHMFL) at Los Alamos has emerged as one of the leading pulsed-magnetic-field research centers in the world, hosting an international user program that attracts around 150 visiting scientists a year to Los Alamos. Part of the NHMFL consortium (which has other facilities at Florida State University and the University of Florida and is jointly funded by the National Science Foundation, the State of Florida, and the Department of Energy), the NHMFL–Los Alamos is a multipurpose facility, powered not only by a 1.4-billion volt-amperes power generator (the country's largest) shown in (a) but also by the intellectual energy of its personnel and user community.

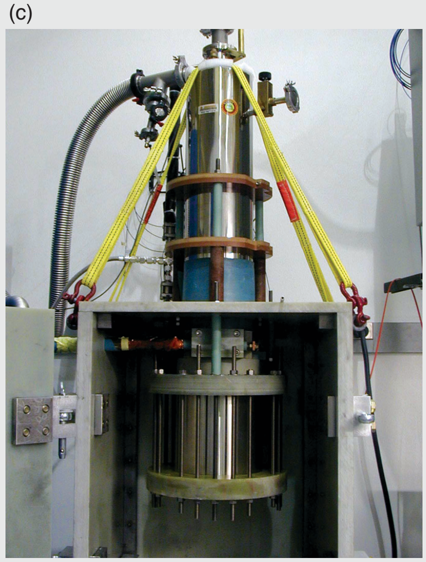
In (b), researchers are shown examining data that come from magnets in cells 3 and 4 of the facility, each of which contains a 60-tesla "short-pulse" magnet that provides a 25-millisecond magnetic pulse. These magnets are the workhorses of the NHMFL user program and are used for magnetotransport, magnetization, and radio-frequency conductivity experiments. Researchers in the background are clustered around cell 2, which contains a 50-tesla "midpulse" magnet, shown in (c), that is primarily used for optics experiments, such as photoluminescence. Another frequently used magnet is the "large-bore" 50-tesla magnet that is used for measurements requiring some "elbow room," such as angle-dependent magnetization and magnetoresistance measurements, or pulse-echo ultrasound and gigahertz spectroscopies.

(a)

(b)



(c)



When energized at peak fields, the different magnets have magnetic energies between 0.5 and 100 megajoules. As a megajoule is roughly the energy equivalent of two sticks of dynamite, research involving high magnetic fields is, in part, an exercise in applied metal fatigue. With pressures in the magnets approaching 1.4 gigapascals (200,000 pounds per square inch), not only does copper wire stretch and rupture, but even garden-variety steels fracture catastrophically. To combat the metal fatigue, the Los Alamos engineers and metallurgists working with the NHMFL have helped to develop a variety of nanostructured conductors and exotic reinforcing materials with greatly enhanced mechanical strength.

The technical expertise needed to maintain the NHMFL magnets is an asset, and it is frequently applied to problems involving pulsed-power, electromagnetic modeling, and other projects that serve the Laboratory's broader mission. The pulsed magnets themselves provide a unique scientific platform for developing and testing experimental techniques in a readily reproducible transient environment. Finally, NHMFL scientists actively collaborate with other Los Alamos researchers on fundamentally important missions ranging from nanoscience to plutonium.

Continued from page 201

that would "see" the neutrino. In 1956, Reines and his team discovered the neutrino using the Savannah River nuclear reactor as the neutrino source. That work opened up the field of experimental neutrino physics, which is still actively pursued at Los Alamos. Recently, Laboratory scientists played a leading role in an international collaboration that presented the first evidence that neutrinos oscillate from one type to another. Such conversion of electron-type to muon-type neutrinos is now believed to solve the solar neutrino riddle—explaining why the number of electron neutrinos detected at the earth's surface is far smaller than the number that solar models predict (see the box "Resolving the Solar Neutrino Problem" on the previous page).

To highlight how ideas in science and technology merge into major programs, we look back to biological research in the 1960s. The principle of flow cytometry—a flow method in which cells are rapidly interrogated one cell at a time—was invented through Laboratory-directed research, and the first device was reported by Mack Fulwyler in 1965 in *Science* (Volume 150). A few years later, Los Alamos flow cytometers could sort cells by DNA content, enabling scientists to study the effects of exposure to radiation or to carcinogenic chemicals, issues relevant to worker safety within the DOE. By 1985, the Laboratory and Lawrence Livermore National Laboratory were sorting the different chromosomes in the human genome with 95 percent accuracy and supplying libraries of cloned fragments for each chromosome to molecular biologists around the world. In the meantime, George Bell, a theoretical physicist formerly in the nuclear weapons program, had founded a unique group in theoretical immunology using LDRD funds. George encouraged his longtime collaborator

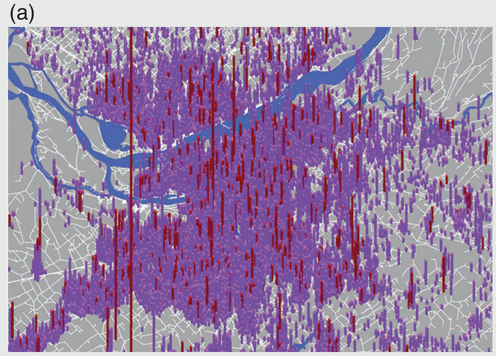
Continued on page 206

EpiSims

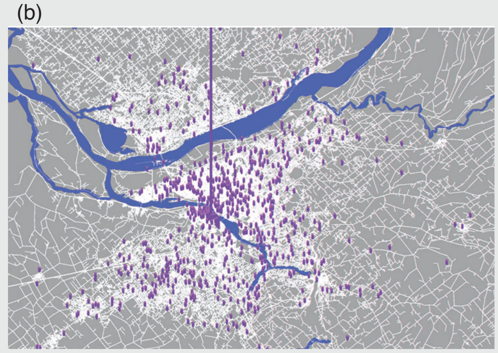
Stephen Eubank

EpiSims is a novel software system for simulating the spread of disease in a large urban population. It is built upon the very detailed models of population mobility provided by UPMoST (Urban Population Mobility Simulation Technology), a simulation system that was also developed at Los Alamos. UPMoST fuses information from different types of data, such as local census data, household activity data, transportation data, and others and uses them to build a synthetic population of individuals who move about an urban region in a realistic network of contact patterns. EpiSims takes this model of population mobility and adds to it models for how disease is transmitted from person to person or contracted from contaminated environments.

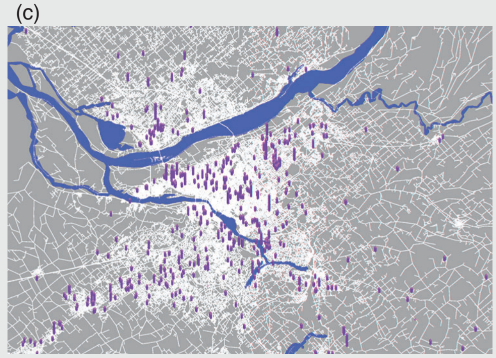
(a)



(b)



(c)

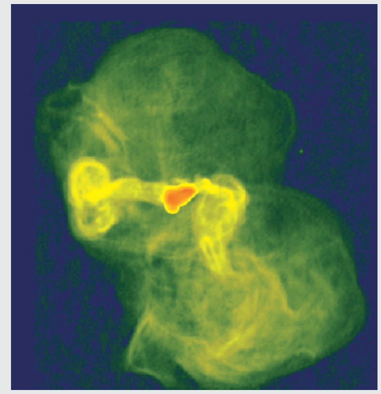


These graphics show the progression of a smallpox epidemic as estimated by an EpiSims simulation. The virus was released among students at a university in downtown Portland, Oregon. Six hours after having been exposed, the infected people—see graphic (a)—have quickly spread through the downtown area. The height of each bar indicates the number of infected people at each location. Graphic (b) shows that, after 40 days, and without a mitigation strategy, the virus has spread throughout the city. The simulation shows that the contagion has touched many demographic groups, so any strategy designed to mitigate the effects of the contagion must accurately take this demographic mixing into account. Graphic (c) shows the viral progression 40 days after the initial infection, but it includes a mitigation strategy that targeted those people who came into contact with contagious people. People who showed symptoms of smallpox were isolated, and their contacts were vaccinated starting 14 days after the attack.

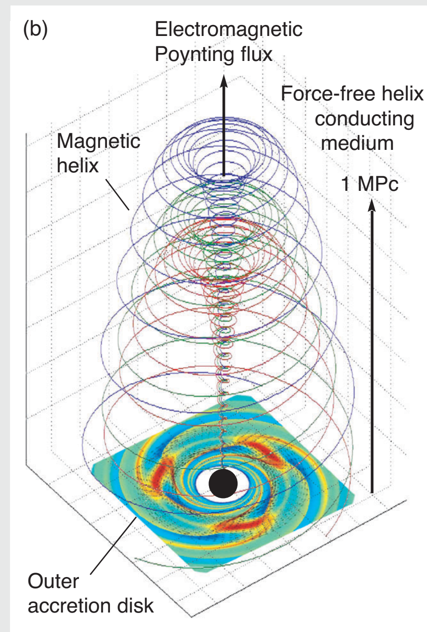
The Magnetized Universe

Hui Li and Stirling A. Colgate

(a)

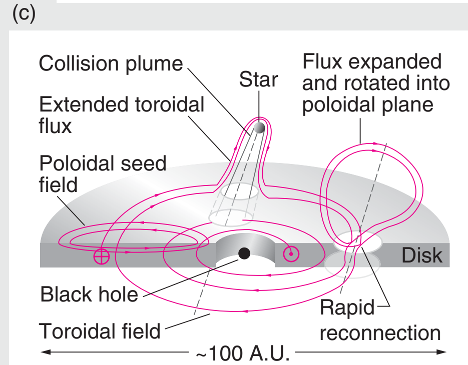


Observations of the cosmos reveal that in the center of most massive galaxies lies a supermassive black hole. These enigmatic objects form by packing 10^8 solar masses into a region the size of our solar system, and roughly 10^{62} ergs of gravitational energy are released during the formation process. A part of this energy is ejected from the region of the black hole as a giant jet or outflow. Such an outflow is visible as the collimated luminous emission in (a), which is a color-coded "radio map" of the giant galaxy M87 in the constellation Virgo. It has been a great challenge to understand the formation of these outflows. Furthermore, where the outflow breaks up, we see radio lobes, which are identified as large regions of space filled with magnetic-field energy and high-energy particles. By studying approximately 100 galaxies with radio lobes, we found that the total energy of the lobes can be up to 10 percent of the energy released when the black hole formed. The identification of this enormous amount of magnetic energy has, among other things, led us to a model of black-hole formation in which gravitational energy is transformed into magnetic energy by a galactic-scale dynamo.



In the early stages of galaxy formation, circulating matter typically forms a disk because of its finite amount of angular momentum. Transporting angular momentum away from the central disk region is essential if the matter is to move inward and collapse to form a supermassive black hole. We have identified a global angular-momentum transport mechanism and performed hydrodynamic simulations to show that large-scale vortices, indicated by colors in (b), can efficiently transport angular momentum outwards. The inner portion of the disk is a conducting plasma that completes roughly 10^{11} revolutions during the 10^8 years it takes for the black hole to form. We propose that a dynamo process will convert that rotational kinetic energy into magnetic-field energy. A cut-away view of the inner region is shown in (c). Because of the differential rotation, the disk twists and amplifies a poloidal "seed" magnetic field (with a radial component in the disk) into a toroidal field. Simultaneously, a large number of stars are swarming in and around the disk, and we expect an exceedingly large number of star/disk collisions to occur during the period of black-hole formation. Each collision makes a plume that transforms a fraction of the enhanced toroidal field back into the poloidal field. Calculations indicate that this process can lead to a positive dynamo gain, allowing the seed field to be exponentially amplified. We are conducting a laboratory experiment using liquid sodium to model this dynamo process.

(c)



Our calculations also show that the fraction of the poloidal field that extends outside the disk is wrapped up by the disk into a force-free helix, carrying away the energy released by the black-hole formation as a Poynting flux—see graphic (b). After tens of millions of years, the helix extends well beyond the galaxy to nearby galaxies. This fact, along with the observation that supermassive black holes are ubiquitous, led us to suggest that a significant fraction of the volume of the universe is filled with magnetic fields. We are still trying to understand how magnetic reconnection can reconfigure those fields and lead to the distorted shapes seen in (a). We are also trying to find out whether our model can lead to the acceleration of the high-energy particles (for example, cosmic rays) and whether, in the ultimate "global warming" scenario, the field heats up the wider intergalactic medium.

Continued from page 204

Walter Goad to follow his visionary ideas regarding molecular biology and start the first data bank (known as GenBank in 1983) for the storage and analysis of DNA sequences. Subsequently, one of George's younger collaborators, Charles Delisi, left Bell's group for an influential position at DOE, and Delisi leveraged those two LDRD-sponsored initiatives, the DNA libraries and data bank, to win DOE sponsorship of the nation's Human Genome Project. The efforts to understand, at a fundamental level, how genomes function have had a direct and continuing impact on our national security. Throughout the 1990s and continuing to this day, technologies from the Human Genome Project have helped combat the threat of biological warfare agents. Rapid DNA analysis tools and miniaturized instruments continue to be developed and fielded for either military or homeland security applications.

As new threats emerge, new areas of science crop up to help mitigate them. A particularly interesting example is the application of quantum mechanical principles to information technology. Richard Feynman recognized that processing information using quantum physics would result in significant differences compared with classical physics approaches. Today, we are witnessing the emergence of a technology based on quantum mechanical principles that can guarantee secure communications. Richard Hughes, originally a postdoctoral fellow in the elementary particles and field theory group, used LDRD funds to start an experimental effort in quantum cryptography, a technique that exploits the properties of single photons to distribute cryptographic keys with guaranteed security against unwanted interception. Hughes and his colleagues made rapid progress and are now supported by programmatic funds. This technology has immediate potential to improve our national security. We do not yet know all the long-term implications of quantum information technology. However, we have a strong sense that continued research in quantum phenomena will play a major role in the technological edge and security of the nation.

These examples of innovation amply demonstrate that intelligent, technically gifted, tenacious people with broad interests create revolutions that change society. But how does an institution identify such creative people, and how long should they be supported to think and explore without constraint? Should a person whose interests do not match the immediate needs or mission of an institution be supported?

The diversity of past success stories tells us that there is no simple answer, nor is there a cookbook recipe. The best one can do is to assign the task to peers, assuming the maxim that it takes one to know one. The system works provided a sufficiently large community exists, whose members, in spite of large egos and a very high degree of competition, value truth and the quest for truth. For many years, the Laboratory has used technical peer review as its decision mechanism when confronted with funding discretionary research. That mechanism produced high standards in the past, and the Laboratory will best succeed in meeting future challenges by sustaining that tradition.

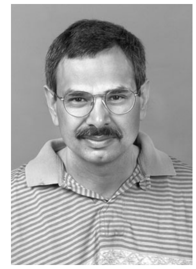
We will also continue to support the Laboratory's vigorous postdoctoral program. It is a superb mechanism for attracting the best young researchers to our programs. Each year, the Laboratory makes a special strategic investment by recruiting about 25 postdoctoral fellows and 6 distinguished postdoctoral fellows through a highly competitive process. The latter group is evenly divided among the J. Robert Oppenheimer, Feynman, and Reines categories. Both these groups of fellows are selected on the basis of academic record, research activities and interests, and leadership potential. They are then supported fully for 2 to 3 years to pursue their own research interests, develop a familiarity with the Laboratory's programs, and investigate ways in which they can match their talents with the needs of the Laboratory. Over time, this program has proved to be extremely successful—a significant fraction of those fellows join programs early in their stay at Los Alamos and eventually become leaders, both as scientists and managers. Furthermore, many of the other outstanding candidates who participate in this competition but are not selected as "fellows" are hired as programmatically funded postdoctoral research associates. The competition is intense, and the combined pool of hired candidates, superb. This approach has ensured the highest possible quality of the technical staff recruited through the postdoctoral program. On average, there are 300 postdoctoral fellows and research associates working at the Laboratory at any one time. Many of them become part of the permanent staff. Those who leave Los Alamos for positions in academia or industry often continue to contribute to our intellectual vitality through collaborations with our staff.

Many of those recruits consider their postdoctoral experience as one of the most productive periods of their lives. As permanent staff, however, they often experience too many constraints on their productive time. Proposal writing, delivery on programmatic milestones, and managing business aspects can take too much time away from creative thinking and innovative problem solving. The Laboratory is working to change this situation. No doubt, from an institutional perspective, the Laboratory needs to hire from among the best and brightest postdocs and hire those who can work effectively on teams, who see the value of multidisciplinary approaches to complex problems, and who can contribute to our diverse work—from fundamental science to pragmatic solutions, and from those to complicated national technology and security needs. But the Laboratory also needs to enable these young scientists to contribute creatively over many decades. The payoffs from basic science are generally long term, and basic science results are seldom accomplished without sustained effort. That effort is possible only through maintaining a good support infrastructure in all the business aspects of the Laboratory and securing stable funding for science.

Historically, very smart people willingly sacrificed their self-interests and worked collectively on projects when they believed in the urgency and importance of the mission. Two outstanding examples of such projects are the Manhattan Project, conducted at a time when eminent scientists understood the danger posed by Nazi Germany and its allies, and the call by President John F. Kennedy in 1961 to put an American on the moon by the end of the decade. Today, we face a similar challenge in the war on global terrorism and on poverty, disease, and diminishing resources. How does an institution retain the capability to respond to such new challenges after years of working on one mission, the stewardship of the nuclear stockpile? Once again, one comes to understand and appreciate the sound judgment and farsightedness of the Laboratory's founders, who put a premium on strategic investment in skilled and talented people and on creating an environment that rewards and nurtures them.

Many of the broad and interconnected challenges being addressed by Laboratory scientists are evident in the topics covered in this section on strategic investments. In the article following this one, for example, Los Alamos scientists discuss how they are using sophisticated mathematical tools to combat HIV, how they determined when the virus entered the human population, and how they came to understand the complex battle that rages between the virus and the immune system. In another article, scientists describe their latest high-resolution techniques for modeling Earth's oceans. The research promises to increase our ability to predict climate change. For the emerging field of nanotechnology, we have developed a new type of laser based on nanometer-size bits of matter, paving the way for ultraefficient optical devices. Other researchers discuss the Laboratory's seminal role in fuel cell research and development as well as our efforts to simulate the flow of water into and out of a regional basin. The Laboratory is strongly committed to supporting an array of activities in basic science to sustain its vitality and meet the long-term challenges of its missions. The boxes accompanying this overview highlight but a few such projects undertaken by the Los Alamos staff.

At this critical juncture in history, we are rededicating ourselves to the pursuit of excellence in science and technology at Los Alamos. We are also finding new ways to communicate to society at large the essential nature of our basic and applied research and give the nation confidence in the integrity of our science and technology. ■



Rajan Gupta graduated from the University of Delhi in 1975 and obtained his Ph.D. in theoretical physics from the California Institute of Technology in 1982. He came to Los Alamos as a J. Robert Oppenheimer fellow in 1985 and is currently the leader of the Elementary Particles and Field Theory Group. He is an elected fellow of the American Physical Society, and his main areas of research are in lattice QCD and the phenomenology of the Standard Model, and in computational physics. He is also deeply involved with accelerating the delivery of education and health care globally and with issues of international security.

David Watkins is a native son, who grew up in New Mexico and obtained a bachelor's degree in physics from New Mexico Tech. He first came to Los Alamos as a graduate student for the summer of 1975, before attending the University of Washington, where he received a Ph.D. in physics. He returned to Los Alamos in 1979 to work on the laser fusion program, developing solid-state nonlinear optical technology. David spent the next ten years of his career as a technical staff member, working on various program—from laser isotope separation to Department of Defense programs. Between 1988 and 1989, David worked at the Royal Signals and Radar Establishment in Malvern, England, as part of a technical exchange for the Strategic Defense Initiative. Upon his return to Los Alamos, he joined the semiconductor physics team in the Electronic and Electrochemical Materials and Devices Group. David served as both deputy leader and leader for that group. In 1999, on April Fools' Day, David joined the LDRD program office and later became LDRD program manager.