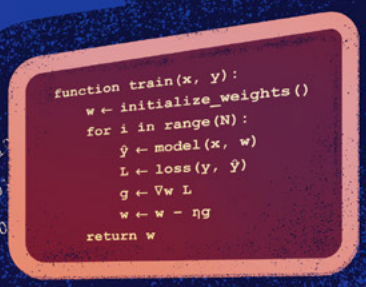
LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE | SUMMER 2026

1663

80+ YEARS OF SCIENCE AND DISCOVERIES



Los Alamos NATIONAL LABORATORY

1663

LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

OUR NAME

During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

COVER: Dan Judge

1663 STAFF

Eleanor Hutterer Editor
Kyle Dickman Science Writer
Rebecca McDonald Science Writer
Jacob Hassett Designer
Dan Judge Designer
Sarah Tasseff Designer
Naveen Velappan Designer
Anne Jones Copyeditor
Jake Bartman Proofreader



6 CHARTING THE FRONTIERS OF THE ATOMIC WORLD

8 Discovery of a Lifetime
11 From Ghost Particle to Cosmic Messenger
15 Fission, Fusion, and the Data Behind Both
18 The Universe's Brightest Mystery



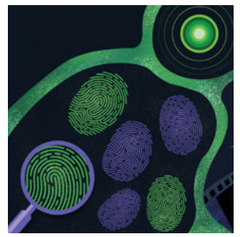
20 POWERING PREDICTIVE DISCOVERY

22 The Science of Unpredictability
25 Big Change for Information Exchange
27 From Monte Carlo to Exascale



30 CONTROLLING PERFORMANCE AT EVERY SCALE

32 Manufacturing the Mission
35 Designing Matter at the Nanoscale
38 A Phase of Its Own
41 Quantum Matters



44 SEEING THE UNSEEN

46 Proton Power for Public Health
50 Flash Photography
53 The Race to Build a Quantum Computer



56 FROM PROTEINS TO PLANETS

58 Fifty Years of Fuel Cell Innovation
61 The Blueprint of Living Things
64 The Planet Inside a Computer
67 The Transparent Earth
70 The Planets
72 Space Science

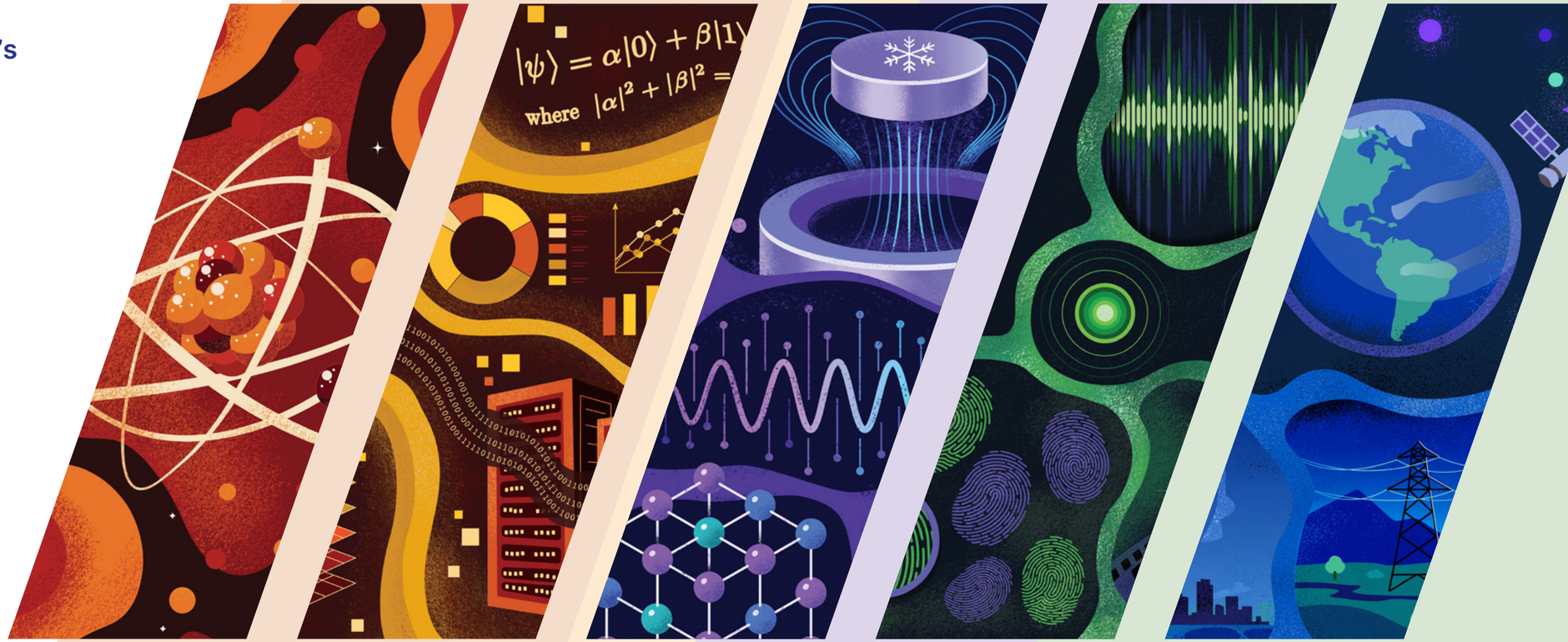
A LEGACY OF DISCOVERY, A FUTURE OF INNOVATION

This special commemorative issue of *1663* celebrates some of the Lab's most notable science, engineering, and technological achievements.

Since its founding in 1943 as a wartime effort and part of the Manhattan Project, Los Alamos National Laboratory has led the world in scientific and engineering discovery. From splitting the atom to modeling the cosmos, science at Los Alamos has shaped how we understand and secure the world we live in.

Our enduring reputation is rooted in the Laboratory's excellence across scientific fields—an intentional cross-disciplinary approach that supports our national security mission and strengthens vital national capabilities. It also pushes the boundaries of human understanding across the sciences. Behind every milestone lies the deep integration of theory, experiment, and simulation that Los Alamos is known for.

Discovery does not occur in a single moment, but along a continuum. At Los Alamos, discovery means pushing boundaries further, asking deeper questions, and building knowledge that transforms the world. From quarks to quasars, from machines to metamaterials, Los Alamos discoveries reflect the fusion of science and security, driving innovation and shaping the future.





"For more than eight decades, bringing theory, experiment, and simulation together has been the hallmark of Los Alamos science—and it's still how we deliver the capabilities the nation relies on."

—Thom Mason, Laboratory Director



"Our strength lies in uniting bold ideas and technical creativity into a single engine of innovation—powering breakthroughs that expand human understanding and address national priorities."

—Pat Fitch, Deputy Laboratory Director for Science Technology & Engineering



"We want to celebrate the numerous remarkable breakthroughs made by our researchers in nuclear science, materials science, computing and algorithms, quantum science, life science, space—the list goes on—and how they complement, and in many cases, support, weapons accomplishments over the years."

—Mark Chadwick, Associate Laboratory Director for Simulation, Computing & Theory



"A lot of effort goes into knowledge transfer at Los Alamos; But our motivation for this project was *inspiration* transfer."

—Bill Priedhorsky, Physicist and Laboratory Fellow

NUCLEAR AND PARTICLE FUTURES:

CHARTING THE FRONTIERS OF THE ATOMIC WORLD

Los Alamos is the nation's premier nuclear science laboratory. Since pioneering the first nuclear weapons and reactors, Laboratory scientists have remained at the forefront of exploring and engineering nuclear phenomena, from the heart of the atom to the far reaches of the universe.

By integrating theory, experiment, and simulation, the Laboratory continues to advance humanity's understanding of nuclear, particle, and cosmic phenomena. Breakthroughs include precise neutron lifetime measurements—key to understanding the matter-antimatter asymmetry question—and the Nobel Prize–winning discovery of the neutrino. Los Alamos leads the field of applied nuclear science, from nuclear safeguards and data files to the discovery of new elements and the exploitation of fusion.



Glowing optical fibers channel light from a Los Alamos detector that measures the free neutron lifetime.

DISCOVERY OF A LIFETIME

REBECCA McDONALD

Los Alamos scientists measured the neutron lifetime with record accuracy.

DESPITE ITS NEUTRAL CHARGE, a neutron's role is hardly benign. Neutrons contribute to the fundamental forces that hold atomic nuclei together. And sometimes they let go, causing the radioactive decay of certain elements and subsequent formation of others.

Shortly after British physicist Sir James Chadwick discovered neutrons in 1932, scientists took advantage of neutrons to induce fission, making them key to the development of nuclear weapons and nuclear energy. Building on this foundation, Los Alamos National Laboratory scientists have spent decades studying the fundamental properties of neutrons to improve their understanding of how elements are formed and how our universe is made.

Particles and forces

The Standard Model of particle physics is a theory describing the particles and forces that make up the universe. To date, it's a fairly comprehensive map of the building blocks of matter and the forces that act on them. The building blocks range from the well-known—electrons, protons, and neutrons—to more recently discovered particles such as quarks and the Higgs Boson. The forces comprise electromagnetism, which acts on charged particles, and the strong and weak forces that hold together atomic nuclei.

The Standard Model is well grounded in experimental evidence and mathematical theory and universally accepted as a pretty good explanation of the building blocks of the universe, however, there are gaps. The Standard Model does not account for dark matter, dark energy, or gravity, and there are lingering questions that continue to tug at scientists' minds. For instance, when studying the Big Bang, models predict that it should have created equal amounts of matter and antimatter, which would have then annihilated each other. However, the asymmetry that resulted (about one extra matter particle for every billion matter-antimatter pairs) is responsible for our universe and all the things we know existing of matter. Evidence beyond the Standard Model—often referred to as extensions to the Standard Model—is all around us, and physicists continue the search for a deeper understanding of the physical world.

Cold and precise

Protons and electrons are understood to be stable, with their lifetimes each exceeding the 14-billion-year-age of the universe. Neutrons, on the other hand, can go through a process called beta decay, during which they devolve into an electron, an antineutrino, and a proton. When neutrons decay within the nucleus of an element, the number of protons in the atom changes, resulting in it becoming a different element.

And when a neutron is free, unattached to any nucleus, it decays, on average, in roughly the time it takes to boil a gallon of water. The exact amount of time was elusive for decades.

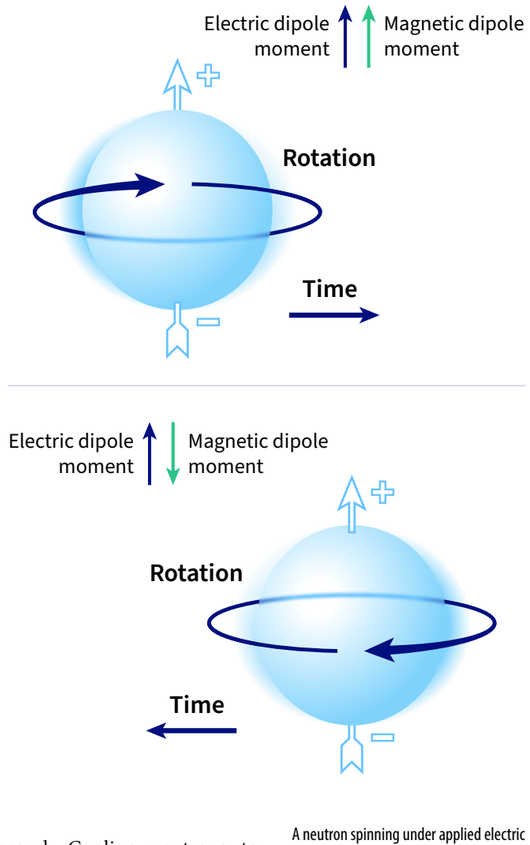
"A reliable neutron lifetime measurement can be used as an input in models of Big Bang nucleosynthesis to help us understand the formation of elements in the early universe," says Lab physicist Steven Clayton. Beyond understanding the Big Bang, neutron lifetime data can be combined with additional measurements to further test the bounds of the Standard Model.

After the neutron was discovered, scientists began trying to measure its lifetime. Over the decades researchers derived several different strategies to measure the lifetime of a free neutron with the highest precision and struggled when their measurements did not match up. For one approach, the number of protons produced in a well-measured beam of neutrons was counted. Another approach used a container to confine ultracold neutrons and measured the fraction of neutrons that survived after given elapsed times. Groups of scientists using these two approaches determined the neutron lifetime to be approximately 887 or 879 seconds, respectively. However, because the two types of measurements were expected to give the same lifetime, but were instead conflicting, scientists at Los Alamos decided to seek a less disputable answer.

A NEUTRON WOULD SPIN COUNTERCLOCKWISE OR CLOCKWISE, DEPENDING ON THE DIRECTION OF TIME.

After the Manhattan Project, Lab scientists continued studying many aspects of nuclear science. In the 1980s and 1990s, several collaborations investigated the fundamental symmetries of the universe, such as the disparity of matter and antimatter, and sought to devise experiments to better understand phenomena such as beta decay. These endeavors led Los Alamos to develop an ultracold neutron capability (UCN) in 1995 in which neutrons are cooled to low temperatures so they move slowly, making them easier to study. Led by Laboratory Fellow Chris Morris (winner of the American Physical Society's 2026 Bonner Prize) the Lab further developed the capability to facilitate a range of precise low-energy particle physics experiments and in 2005 the UCN began operating as an international facility. The Laboratory's UCN Source is now considered one of the highest intensity UCN sources in the world. This capability made it possible for Los Alamos to take the lead on measuring neutron lifetimes.

The UCN Source uses a solid deuterium crystal to cool neutrons energies to about 1 millikelvin (one-thousandth of a degree above absolute zero), so that they move at speeds of only a few meters per second. Cooling neutrons to "walking speed" enables them to be completely confined by magnetic fields and gravity. Taking advantage of this unique capability, Los Alamos scientists developed a new kind of neutron-lifetime experiment by building a magnetogravitational trap, a container resembling a bathtub whose concave surface is covered in magnets and the top is open. Using this trap, the team set a record in 2021 when they measured the neutron lifetime to 877.75 seconds, cutting the uncertainty of the previous best measurements in half.

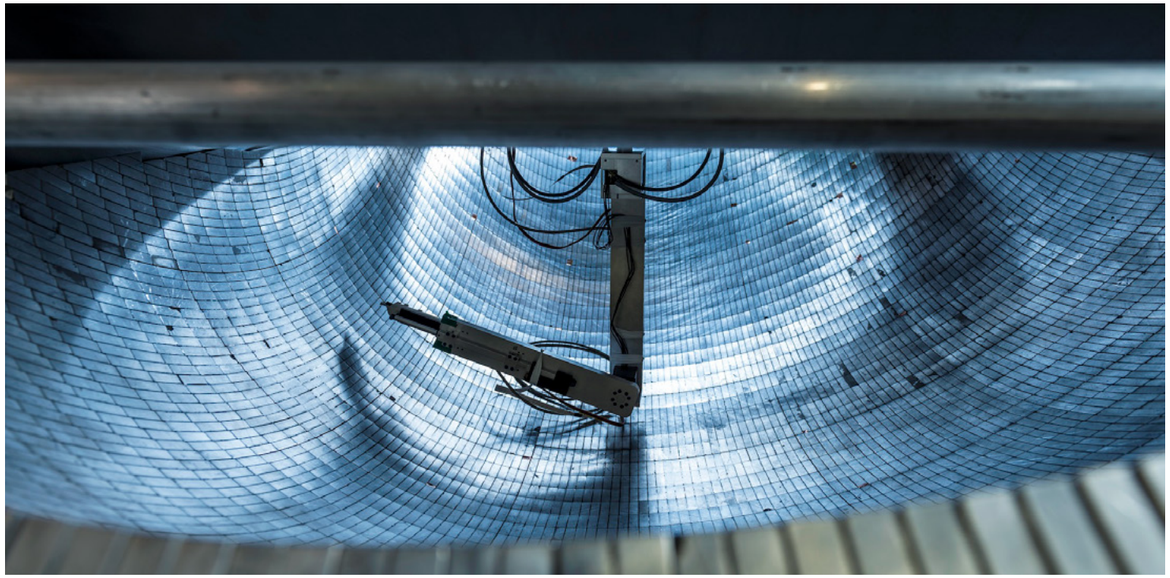


A neutron spinning under applied electric and magnetic fields. Its magnetic dipole moment (MDM) is nonzero, and if its electric dipole moment (EDM) is also nonzero, and you reverse time, the neutron's spin precesses at different rates.

Then, in 2025, the team analyzed an additional three years of data and updated the measurement of a neutron's lifetime to 877.83 seconds, with uncertainty reduced to under 0.3 seconds.

Beyond what is known

The LANSCE UCN Source attracts collaborators from more than 20 universities across the United States and Europe, helping them play leading roles in fundamental neutron physics efforts



A trap for ultracold neutrons with a calibration probe used to map its magnetic field. Measurements with the trap set a record for the most precise measurement of neutron lifetime.

at other institutions. And, in addition to experimental research, several Los Alamos theoretical physicists are evaluating the results of neutron and other particle experiments to both speculate about what is possible and to analyze what has been observed.

One UCN project is to measure the correlation between the spin of a beta-decaying neutron and the resulting electron. When this measurement is combined with the precise neutron lifetime, the self-consistency of the Standard Model can be tested, allowing scientists to identify limits on extensions to the Standard Model that could explain other phenomena such as new properties of known or hypothetical particles.

"THE NEDM EXPERIMENT AT THE LANSCE COULD WELL ANSWER QUESTIONS ABOUT THE ORIGIN OF THE UNIVERSE."

"Further improvements to these measurements could someday lead to a new Standard Model of particle physics," says Clayton.

Another project that is currently underway is the Los Alamos Neutron Electric Dipole Moment (nEDM) experiment, which not only challenges the Standard Model, but could also lead to a better understanding of the origin of the matter-antimatter balance of the universe.

"We want to understand if the laws of physics are the same if time runs backwards," explains Los Alamos physicist and Lab Fellow Tom Bowles. In other words, consider a film of two billiard balls colliding. If you watch the film played forward or backward, you can't tell the difference. However, if the balls were neutrons, and one had a nonzero EDM, it would look different being played forward versus backward.

The electric dipole refers to the separation of positive and negative charge within a neutron. The nEDM is vanishingly small in the Standard Model: If the neutron were the size of Earth, the charge separation would be about the thickness of a human hair. In spite of how difficult it is to detect, some theoretical extensions to the Standard Model suggest a nonzero EDM could be measurable.

At the LANSCE UCN Source, Los Alamos scientists are working to improve on past nEDM experiments by using high-precision nuclear magnetic resonance (NMR) measurements of stored UCNs with a strong electric field applied along or opposite the applied magnetic field. If the NMR signal frequency changes when the field is reversed, that would indicate a nonzero EDM.

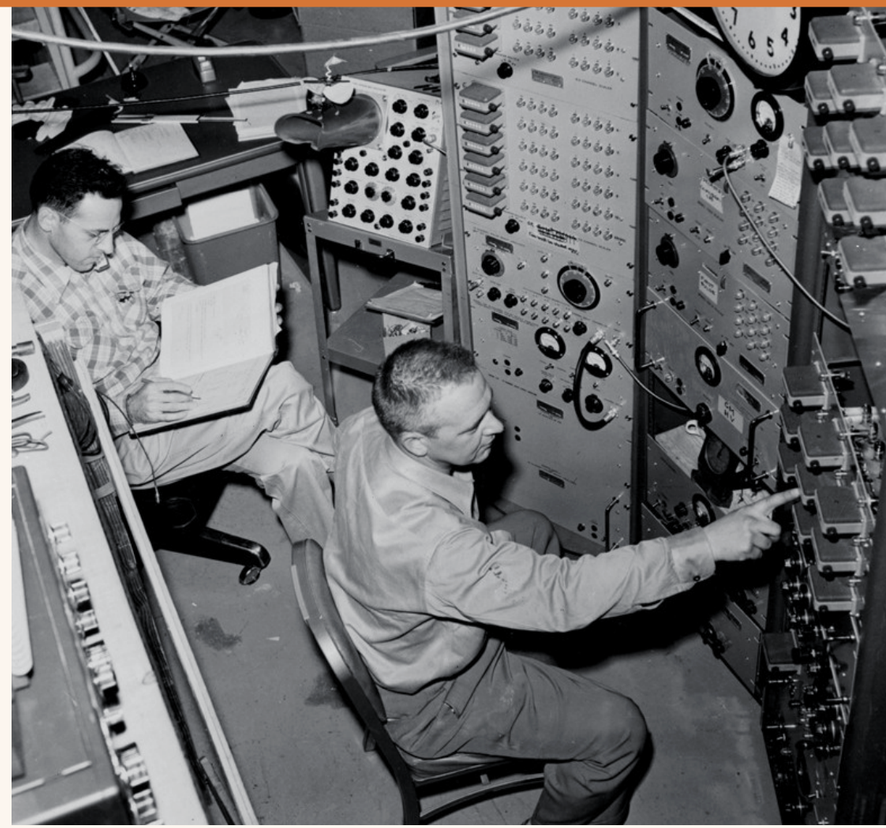
In our four-dimensional universe (x, y, z, and time) our best theory tells us that differences between left and right, matter and antimatter, and time reversal need to all balance out. But high-energy physics data don't support that theory. Measuring a nonzero nEDM could help answer these questions about asymmetery.

"Because time reversal is related to the matter-antimatter balance in the universe, a nonzero nEDM measurement could explain the asymmetry in matter and antimatter. The nEDM experiment at the LANSCE could well answer the question of why we are here," says Bowles. ■

FROM GHOST PARTICLE TO COSMIC MESSENGER

ELEANOR HUTTERER

Los Alamos has a long legacy of neutrino science.



Fred Reines and Clyde Cowan at the controls of the Savannah River experiment in 1956.

By 1970, fourteen years after Los Alamos scientists first proved the existence of the neutrino, they knew something was amiss: an underground neutrino experiment built inside the Homestake Mine, an enormous active gold mine in South Dakota, was detecting way fewer neutrinos coming from the Sun than scientists had predicted, and they didn't know why.

Neutrinos are famously elusive elementary particles. They are electromagnetically neutral and nearly massless, making them extremely hard to detect. These particles continuously and innocuously rain down on Earth from the Big Bang and sources in space. And they come in three varieties, called flavors—electron, muon, and tau.

"Either we didn't understand the Sun, or we didn't understand neutrinos," recalls Thomas Bowles, retired Los Alamos physicist and Laboratory Fellow.

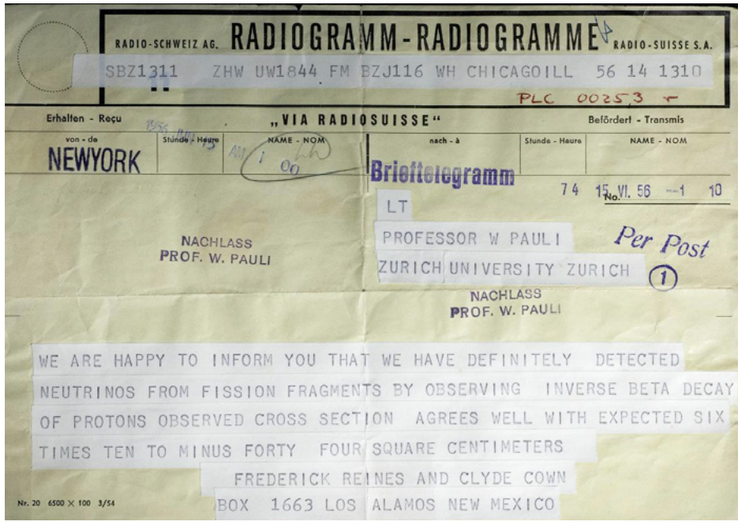
Bowles was lead on the Soviet-American Gallium Experiment (SAGE), a government-to-government collaboration launched in 1987 to figure out what was going on with the Homestake experiment's data. As it turns out, the Sun was behaving as expected; the neutrinos were playing tricks. SAGE data showed that something was happening to solar neutrinos after production and before detection that caused the detected number to be lower than expected. Scientists proposed that the data could be explained by oscillation—neutrinos changing between flavors as they raced through space.

This would mean neutrinos are doubly elusive: not only do they hardly interact with anything, including detectors, but they also shapeshift. "It's like a ghost in a white coat enters a room then suddenly the coat flips to black," laughs Bowles.

Catching the ghost

Known physics was breaking down in the 1920s, and the neutrino fixed it. Physicists studying radioactive decay of atomic nuclei were seeing data that violated the principle of energy conservation. They theorized an undetected particle with specific properties—electrically neutral and nearly massless—that would make sense of the data. Inventing an invisible thing to precisely fill a specific gap was, they admitted, a desperate remedy. But once a new theory was drafted that included the neutrino, suddenly the math worked and the data made sense—the cosmic books were balanced.

Just because neutrinos fit the data did not make them real. Neutrinos, if they existed, were predicted to interact so weakly that tens of quadrillions would need to pass through a detector before just one was detected. At Los Alamos in the 1950s, nuclear weapons and nuclear reactors were central areas of research, either of which, reasoned Lab physicists Fred Reines and Clyde Cowan, might produce enough neutrinos to catch one. Reines and Cowan explored both areas and in the end took a custom-built detector to the nuclear reactor at South Carolina's Savannah River Plant in 1956, and made the catch. Specifically, they detected electron antineutrinos—the antiparticle of the electron neutrino, whose very existence proved the existence of the other. Cowan passed away in 1974, and Reines received the Nobel Prize in Physics in 1995 for their discovery.


RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de NEWYORK Stunde - Heure NAME - NOM

nach - à Stunde - Heure NAME - NOM

Briefteleqramm

74 15.VI.56 —1 10

No.

NACHLASS PROF. W. PAULI

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

(1)

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

When Los Alamos scientists Fred Reines and Clyde Cowan proved the existence of neutrinos in 1956, they sent this telegram to Wolfgang Pauli, who had first proposed the theoretical particles 26 years earlier, informing him that he had been right.
CREDIT: European Organization for Nuclear Research (CERN).

NEUTRINOS ARE DOUBLY ELUSIVE: NOT ONLY DO THEY HARDLY INTERACT WITH ANYTHING, INCLUDING DETECTORS, BUT THEY ALSO SHAPESHIFT.

Once neutrinos were real and scientists had ways to detect them, more specific questions could be pursued, like what is their miniscule but non-zero mass? Neutrino mass experiments do not weigh neutrinos directly; they set limits. Tiny distortions in the data indicate where observations deviate from what would be expected with massless neutrinos, pointing to upper limits of mass, rather than precise values.

However, in the 1980s, Soviet scientists reported a measured mass—not just an upper limit—of the electron neutrino to be around 26 electronvolts (eV). The claim shook the neutrino community and threatened to rewrite cosmology. If true, it would "close the universe," meaning it would ascribe enough mass and energy to the universe to eventually halt its expansion and reverse it. Los Alamos scientists, including Bowles and his colleague Hamish Robertson, another physicist, made their own measurements using gaseous tritium. (The Soviets had used tritium too but as part of a complex molecule rather than a simple gas.) The Los Alamos team came back with a maximum mass of less than 9.3 eV—far below the claimed measurement and not enough to close the universe.

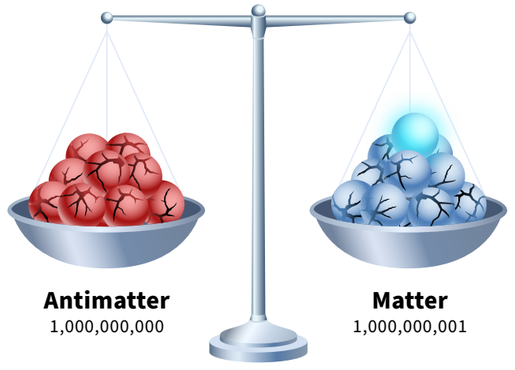
While the Soviet and Los Alamos scientists worked independently to measure mass, the SAGE collaboration to observe solar neutrinos was underway. SAGE was born, essentially, from a shared inventory list for a neutrino experiment. "We needed something like 60 million dollars' worth of gallium metal to build neutrino detectors," recalls Bowles. "Which we didn't have. But the Soviets did. They also had an underground lab and a village to support it. What they didn't have was the computers and high-end electronics they needed. Which we provided. It was a really good marriage, scientifically." Indeed, as well as predicting neutrino oscillation, the SAGE data set a new mass limit for the electron neutrino at under 1 eV, leaving the universe decidedly unclosed.

One in a billion

As alluring as they are enigmatic, neutrinos spur speculation around big questions—like why we are here at all. Some physicists think neutrinos may hold the key to the matter-antimatter asymmetry problem: why the universe is made of matter. The Big Bang should have created equal amounts of matter and antimatter, which would have annihilated each other completely. But the slight imbalance of about one extra matter particle for every billion matter-antimatter pairs allowed matter to survive and form everything we know, from protons to planets to people.

The fact that anything remains after matter-antimatter annihilation is one of cosmology's deepest puzzles. The Standard Model, science's best theory for describing fundamental particles and their behavior, cannot adequately explain the cause of the asymmetry. The model is spectacularly successful at predicting particle physics to extraordinary precision, but it is incomplete—while its core structure is stable, its parameters are under constant refinement. For example, the model originally assumed neutrinos were massless, which oscillation experiments disproved. Because neutrino mass requires physics beyond the minimal Standard Model, physicists suspect neutrinos may hold additional clues—possibly even the cause of matter-antimatter asymmetry. The question is no longer whether new physics exists in the neutrino realm, but how much more is hiding there.

When something in nature seems hidden or doesn't add up, scientists build experiments to reveal what's missing. The flagship Los Alamos neutrino experiment, the Liquid Scintillator Neutrino Detector (LSND), ran in the 1990s to test whether muon neutrinos could oscillate into electron neutrinos over a short distance—a pattern the Standard Model could not easily accommodate. LSND data was consistent with such oscillations, pointing to physics beyond the three known neutrino types and providing the first hint at what would come to be called sterile neutrinos. Whereas active neutrinos are nearly inert, interacting with matter only through a fundamental force called the weak force, sterile neutrinos would be truly inert, subject only to gravity. An active neutrino oscillating into a sterile neutrino would to a detector look like the neutrino disappeared. And neutrino experiments had previously seen neutrinos seeming to disappear from experimental data streams, so the sterile neutrino theory made sense.



The matter-antimatter asymmetry problem cuts to the question, why are we here? According to known physics, the universe ought to have annihilated itself. The Big Bang should have produced matter and antimatter in equal quantities, and their mutual annihilation should have left behind only energy. Yet matter won by a hair—about one part in a billion survived. That one part is not predicted by the Standard Model but comprises everything: galaxies, planets, people. Some physicists suspect neutrinos helped tip the balance—but no one has proved it. Yet.

Since the LSND experiment, more clues have come in from experiments around the world that point to the existence of sterile neutrinos. Similarly, clues have come in that refute it. In 2007, the MiniBooNE experiment at Fermilab first disagreed, then agreed with LSND. A follow-on experiment, called MicroBooNE, was built specifically to look for sterile neutrinos, and in late 2025, it reported no evidence of the expected signatures. But absence of evidence is not evidence of absence. Every neutrino experiment looks for a specific phenomenon in a specific way, so just because they have not found it, doesn't mean they won't. One by one, contradictory results are narrowing the range of possibilities. What has not been refuted is that the data suggest lingering mysteries, potentially involving dark matter or other exotic particles. Once again, new physics is needed to make it all add up.

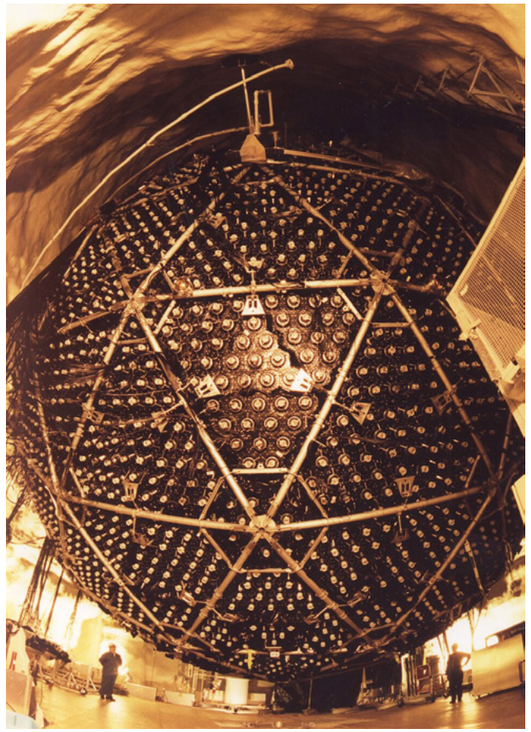
KNOWN PHYSICS WAS BREAKING DOWN IN THE 1920S, AND THE NEUTRINO FIXED IT.

The dark sector

Particles that do not interact and the black-box nature of the physics afoot has led physicists to posit a "dark sector," a hidden extension of particle physics that includes weakly coupled particles and forces. Dark matter is the most famous resident of the dark sector.

Still hypothetical in the sense that it is not well understood, dark matter is accepted as real because many independent observations require it. Whereas about 5 percent of the universe is ordinary matter—atoms, galaxies, sandwiches—27 percent is dark matter. (The remaining 68 percent is thought to be dark energy, a mysterious something that does not behave like matter and is accelerating the expansion of the universe). Scientists believe that dark matter is real, massive, electrically neutral, gravitationally active, and weakly interacting. But what it's made of is a mystery. Maybe it's sterile neutrinos.

In 1990, Los Alamos joined the Sudbury Neutrino Observatory (SNO), an underground neutrino experiment in Canada designed to pick apart the solar neutrino question. The Homestake experiment and SAGE had measured the solar neutrino deficit and SNO wanted to explain it. SNO showed that electron neutrinos oscillate into muon and tau neutrinos, and Los Alamos played a key role by providing an independent method of measuring all three types of neutrinos. When all



Exterior of the original Sudbury Neutrino Observatory detector, located two kilometers underground in Ontario, Canada. The acrylic sphere held 1000 tons of heavy water and was lined with 9500 photomultiplier tubes. *CREDIT: SNO Collaboration / Berkeley Lab.*

flavors were measured together, the solar output was as expected—the deficit only appears when neutrinos are measured by flavor.

Whereas previous mass estimations had placed increasingly stringent upper limits on neutrino mass, SNO was the first to actually make a mass determination, showing that neutrinos must have a mass around 1 millielectronvolt (meV), which is about a billion times less than a single electron. But even with this miniscule mass, because of sheer numbers, neutrinos still account for 5 percent of the mass of the universe. SNO director Art McDonald was awarded the 2015 Nobel Prize in Physics, and he invited Robertson, who developed the independent measurement capability, to attend the ceremony.

SNO's findings indirectly nudged dark matter theory toward sterile neutrinos. If active neutrinos account for 5 percent of the total mass budget, they alone cannot account for dark matter, which makes up 27 percent. Sterile neutrinos could be the missing mass.

Lighting a path

Los Alamos continues to participate in large, international neutrino collaborations. Right now, the Lab is collaborating on the LEGEND project, deep below a mountain in Italy, where the neutrino detectors are shielded from cosmic ray backgrounds. Working underground, the Lab's expertise in high-sensitivity detectors and low background environments has been foundational for LEGEND.

LEGENDS's scientists are looking at the matter-antimatter asymmetry problem in a new way, specifically asking if neutrinos could be Majorana particles—particles that are their own antiparticle. If they are, these particles would violate the accounting rules of particle physics and offer a mechanism for matter to have persisted. Neutrinos have already forced physicists to rewrite the rules; this could be another rule that neutrinos are breaking. To check for Majorana behavior, the LEGEND project is looking at a nuclear decay process called double beta decay, during which an atomic nucleus changes to a different element by converting two neutrons into two protons. As byproducts, the nucleus emits two electrons and two antineutrinos. If neutrinos are their own antiparticle, then the two antineutrinos will instantaneously annihilate, leaving only the emitted electrons.

THE QUESTION IS NO LONGER WHETHER NEW PHYSICS EXISTS IN THE NEUTRINO REALM, BUT HOW MUCH MORE IS HIDING THERE.

Whether LEGEND detects neutrinoless double beta decay or not, it will constrain the possibilities in a useful way. If detected, the Standard Model cracks open and scientists can open the door to extending the model to include Majorana particles. If not detected, scientists can close the door on most Majorana models, shrinking the range of possibilities. Either way, it's progress.

The neutrino story at Los Alamos is a story of stubborn questions, diverse detectors, and collaboration. "It's really about breadth of knowledge," says Bowles. "Basic science answers a lot of fundamental questions that the weapons program and national security programs need answered. Our world-leading science brings the brightest minds here, and once they're here, they engage with all sorts of important questions."

Neutrinos have never behaved the way physicists expected them to. They were invented to fix a bookkeeping problem and continually refuse to fit cleanly into the Standard Model. For seventy years, they have pulled Los Alamos scientists into collaborations that span continents and generations. And they still refuse to add up, pushing new questions. Either way, the story hasn't ended. ■

FISSION, FUSION, AND THE DATA BEHIND BOTH

ELEANOR HUTTERER



In 2022 a huge step toward fusion energy was achieved at the National Ignition Facility. For the first time scientists were able to get more power out of a fusion reaction than went into it, a vital step known as "ignition." Here a mix of deuterium and tritium is contained in a pellet the size of a peppercorn while powerful lasers heat and compress the pellet.
CREDIT: Lawrence Livermore National Laboratory

Decades of Los Alamos discoveries, from the birth of fission to the edge of fusion.

EVERY TIME A REACTOR STARTS UP, A FUSION PLASMA burns, or a nuclear-powered spacecraft ventures into deep space, Los Alamos science is at work—the enduring influence of the Laboratory that has shaped the nuclear age from its first spark.

"Los Alamos has been and remains the nation's leader in applied nuclear science," says Mark Chadwick, Associate Laboratory Director for Simulation, Computing, and Theory and former Chief Scientist for Weapons Physics. "We've made iconic breakthroughs that range from definitive measurements in fission and fusion to nuclear databases and modeling methods that are used around the world."

Best known for developing the world's first nuclear weapons, Los Alamos also developed some of the first nuclear reactors, nuclear rockets, and remote-sensing satellites. For more than 80 years, Laboratory scientists and engineers have built an entire infrastructure of applied nuclear science with the aim of understanding nuclear power so completely that humanity can wield it wisely.

Nuclear weapons

The Laboratory was founded in 1943 as the U.S. Army's central laboratory for the top-secret effort to develop atomic bombs. In those early days, the Lab's applied nuclear technology encompassed plutonium purification, weapons-core fabrication, criticality experiments, and bomb design for deployment.

Two years in, by integrating theory, experiment, and engineering, and drawing together many of the era's leading scientists and engineers, the Lab delivered two distinct atomic weapons: a gun-type device that drove one piece of uranium into another to create a critical mass, and an implosion-style device that used precisely timed explosives to compress a plutonium core to criticality. Although they used different materials and different designs, both weapons exploited the phenomenon of nuclear fission, whereby heavy atoms, like uranium and plutonium, are split into multiple smaller nuclei. First the atom absorbs a neutron which makes it unstable. Then it splits and releases more neutrons, which get absorbed by neighboring atoms, causing them to also split, thereby initiating a rapidly multiplying chain reaction.

Scientists knew that while the splitting of heavy atoms could release tremendous energy, the merging of light atoms—fusion—could release much more. But it would take the power of fission to force fusion to occur. So, having created fission-based weapons, the Lab's attention was next fixed on fusion-based weapons.

At Los Alamos in 1945, British physicist Egon Bretscher showed that the fusing of deuterium and tritium, both isotopes of hydrogen,

had an unexpectedly large cross section, meaning those nuclei were more likely to fuse with one another than with any other nuclei. The cross section was so large as to dwarf all other fusion reaction cross sections at comparatively low energies. This phenomenon was attributed to the excited state of the compound nucleus formed, which quickly decays into a helium nucleus and a neutron. Bretscher correctly predicted this reaction—the fusion of deuterium and tritium—would make fusion technologies feasible.

Fusion-based weapons, or thermonuclear weapons, release many times the energy of fission-based weapons, in part because of fuel efficiency. Fusion fuel nuclei are small and light, while fission fuel nuclei are large and heavy, meaning a single gram of fusion fuel contains many more atoms than a gram of fission fuel, so many more energy-releasing reactions occur within the same mass of fuel.

Nuclear power

Fusion energy drives the sun and stars, and the excited state of the compound nucleus that Bretscher discovered, now known as the "Bretscher state," underlies nearly every major branch of applied fusion science—well beyond nuclear weapons.

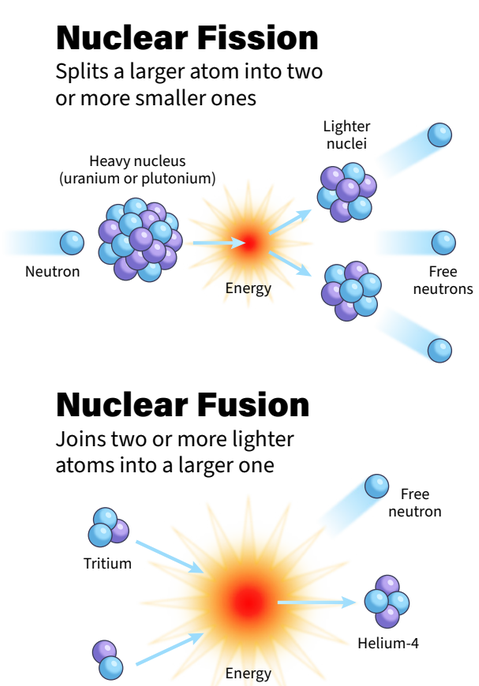
SCIENTISTS KNEW THAT WHILE FISSION—THE BREAKING UP OF HEAVY ATOMS—COULD RELEASE TREMENDOUS ENERGY, THE MERGING OF LIGHT ATOMS—FUSION—COULD RELEASE MUCH MORE.

"It all comes down to an accident of nature," explains physicist and Laboratory Fellow Bill Priedhorsky. "If you look at various things that fuse, you get these cross sections, and at the right temperature, deuterium and tritium are much more likely to fuse than anything else."

Because fusion can produce roughly four times more energy per kilogram of fuel than fission and nearly four million times more energy than burning coal, it was of keen interest to the energy sector. Through the 1950s, '60s, and '70s, as different countries pursued fusion for energy, deuterium-tritium (DT) fusion was at the center of most designs. Magnetic confinement machines were built to hold a burning DT plasma using magnetic fields. Inertial confinement machines were built to heat and compress DT fuel pellets with lasers. The Lab even explored fusion-powered rockets for planetary defense. But it's tough to create, confine, and control the power of the sun, and fusion for energy has faced engineering and technical challenges.

Although still in the research phase, interest in fusion energy is growing, momentum is building, and gains are being made. In 2022, a collaboration between Los Alamos and Lawrence Livermore National Laboratory achieved ignition, getting more energy out of a fusion experiment than went into it for the first time ever, tantalizing humanity with the dream of clean, safe, and endless energy.

Nuclear reactors that use fission, on the other hand, are well established and have powered cities, submarines, and spacecraft for decades. Nuclear energy is a key part of the Lab's mission space. The official first fission reactor in the world, led by Enrico Fermi in 1942, proved the concept of a controlled fission chain reaction for the Manhattan Project. The first nuclear reactor in the world to generate usable electricity was the Experimental Breeder Reactor-I in Idaho in 1951. All the foundational knowledge—like neutron transport theory, cross-section measurement capability, and criticality safety procedures—needed for nuclear power plants came straight from Los Alamos's wartime and postwar nuclear research. And as nuclear know-how grew, the scope of fission energy broadened to include nuclear reactors for machines on the move.



Nuclear fission and nuclear fusion both release energy, but they do it in different ways. (Top) In fission, a heavy nucleus such as uranium-235 absorbs an incident neutron and becomes unstable, then splits into two lighter nuclei, releasing additional free neutrons and energy. The emitted neutrons can initiate further fission events in nearby nuclei, creating a chain reaction. (Bottom) In fusion, two light nuclei—typically the hydrogen isotopes deuterium and tritium—combine under high temperature and pressure to form a heavier nucleus, like helium-4, releasing a free neutron and energy. Fusion relies on maintaining extreme thermodynamic conditions, rather than creating a chain reaction.

THE MODERN LAB IS BOTH INNOVATOR AND SENTINEL—ADVANCING NUCLEAR SCIENCE WHILE ENSURING SAFEGUARDS AND DETERRENCE.

It didn't take long to realize that nuclear power could be ideal for military submarines, providing virtually limitless power underwater without the need to surface. The U.S. Navy–led mission to create the first nuclear-powered submarine drew heavily on Los Alamos science. The product, the USS Nautilus, launched out of Connecticut in 1955 and traveled thousands of miles without surfacing, staying submerged for weeks on end. In 1958, after numerous successful voyages, she became the first vessel to reach the North Pole underwater.

Once compact nuclear power systems were proven to work reliably away from land, the next frontier was space. Project Rover was a joint effort between Los Alamos and the Atomic Energy Commission to build fission-powered rockets. In 1961, the project demonstrated that nuclear propulsion in space was not only feasible but could outperform chemical propulsion by a factor of two. A flight-ready, full-scale nuclear rocket engine was even demonstrated by project NERVA, the NASA-led follow-on to Rover, in 1972. But by then, Apollo 11 had put the first humans on the moon and no other immediate NASA mission required a nuclear rocket, so the work was shelved.

Most recently, Lab scientists have developed a compact, autonomous system called Kilopower, which could one day power human habitats on Mars and deep-space missions. For Earth-bound applications, the technology is being miniaturized to fit inside a shipping container to create standalone mobile power plants that can travel almost anywhere. Los Alamos scientists are even reimagining nuclear power all together, developing a whole new paradigm of molten-salt nuclear reactors, which recycle fuel, cut waste, and could be hundreds of times more fuel-efficient than current solid-fuel, water-cooled designs.

Stockpile modernization

As scientists have found new ways to use nuclear science to power discovery, weapons research has continued, and Los Alamos remains a pillar of the U.S. nuclear-weapons enterprise. The Lab's approach to the design, certification, and assessment of the nation's nuclear weapons includes top-notch computer simulation and experimentation.

To support simulation, the Lab invested heavily in computational capabilities, supercomputing, and physics modeling of weapons systems and nuclear materials. To support experimentation, the Lab used its world-class neutron facility LANSCE, to deliver nuclear cross sections with unprecedented accuracy. Other types of experiments, particularly criticality experiments, were moved to Nevada and consolidated into the National Criticality Experiments Research Center (NCERC) under Los Alamos leadership. The NCERC is a direct descendent of the weapons work at Los Alamos and is the nation's only facility capable of performing general-purpose critical experiments.

"These experiments provide accurate integral criticality data that allow us to validate and improve our simulation capabilities," explains Chadwick. "Indeed, these simulations are calibrated to match the precise NCERC data."

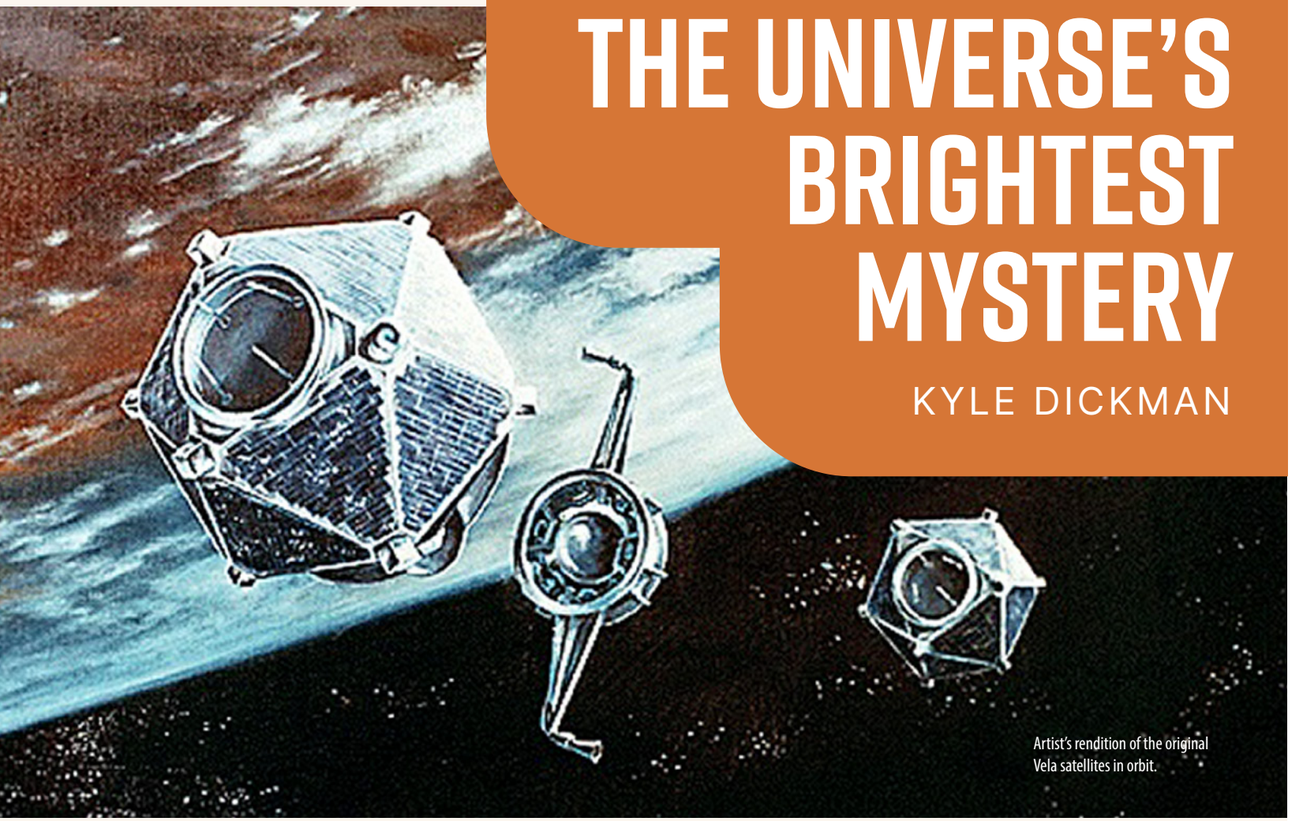
Data from decades of supercomputing simulations and criticality experiments are kept in a database called the Evaluated Nuclear Data File (ENDF). This is the national repository of all the nuclear data that are needed to correctly integrate experimental results and theoretical simulations in support of the nation's modern nuclear stockpile.

Internationally, Los Alamos promotes global security and nonproliferation by helping to establish nuclear safeguards for the International Atomic Energy Agency (IAEA), training all IAEA inspectors, and developing advanced detectors. Importantly, the MCNP code, the world's most accurate and popular particle transport code, still used widely across national laboratories, universities, nuclear facilities, defense organizations, and private industry, is also a Los Alamos discovery.

Though the Lab's nuclear-weapons legacy remains central, applied nuclear science at Los Alamos today reaches far beyond stockpile readiness, encompassing energy work, nuclear materials science, nuclear nonproliferation, and arms control. The modern Lab is both innovator and sentinel—advancing nuclear science while ensuring safeguards and deterrence. Los Alamos undeniably remains the Laboratory that knows the atom best. ■

THE UNIVERSE'S BRIGHTEST MYSTERY

KYLE DICKMAN



Artist's rendition of the original Vela satellites in orbit.

Los Alamos scientists turned nonproliferation instruments into tools of cosmic revelation.

In 1963, some eighteen years after the world entered the atomic age, a pair of national security satellites launched from a low, sandy peninsula in Florida called Cape Canaveral. The Velas, as they were known, were the first in a series of far-seeing sentinels built by Los Alamos scientists that were capable of spotting high-energy terrestrial events from orbit. But while the scientists' attention was fixed on Earth, the Velas were quietly collecting data that would redefine astrophysics and cement Los Alamos's role in global space science.

Each Vela carried detectors tuned to x-rays, gamma rays, and neutrons—the signatures of nuclear detonations. Scientists knew gamma rays—the most energetic form of light—appeared fleetingly during weapons detonations, as a byproduct of nuclear fission. The idea that such radiation could arise naturally in the cosmos, through any processes understood at the time, seemed inconceivable. "You have to be very, very hot to get gamma rays," says Ed Fenimore, a Los Alamos astrophysicist and Laboratory Fellow. "We're talking extreme conditions where gas clouds, or at least individual particles, have energies corresponding to billions of degrees."

Then, in 1967, the Vela's sensors lit up with brief, intense bursts of gamma radiation. The flashes were unlike anything the Vela team expected. On the gamma-ray curve, instead of a single, sharp, microsecond-scale pulse, they rose and fell irregularly over seconds or even minutes. "A nuclear weapon goes up sharp and comes down sharp," Fenimore says. "These went spike, spike, spike … hiccup… and then off, never to repeat." Somewhere in the universe, something was generating energy beyond anything known to humanity before.

After a few years spent ruling out any other explanation, in 1973, Ray Klebesadel, a Los Alamos physicist, published a paper announcing the discovery of gamma-ray bursts, or GRBs, that came from deep space. The paper, which reported on 16 Vela events, became one of astrophysics' most influential publications and launched a global race to explain GRBs. "Where were gamma rays coming from?" Fenimore asks. "What natural process could make them?"

The mystery played a key role in the rise of high-energy astrophysics: the study of x-rays and gamma rays from cosmic sources. Throughout the 1970s and '80s, Los Alamos led the new field, designing and building instruments for satellites worldwide and then analyzing the data. Each new generation of satellites and detectors strengthened Los Alamos's role in high-energy astrophysics. Yet GRBs themselves remained elusive.



President Kennedy pictured with a mock-up of a Vela satellite in 1962. Kennedy visited Los Alamos National Laboratory shortly after this picture was taken.

As the search for GRBs became more sophisticated, it attracted new scientists, including Fenimore, who joined the Lab in 1974 and quickly became one of the central figures working on the GRB mystery. He developed a novel imaging technique that allowed bursts to be pinpointed more precisely. "The name of the game was location," he says. "If you could figure out which star was doing it, maybe you could figure out how."

By the early 1990s, the National Aeronautics and Space Administration (NASA) had intensified the pursuit of this goal by launching the Compton Gamma Ray Observatory—the gamma-ray-focused sister to the optical Hubble Space Telescope. It mapped hundreds of bursts. To everyone's surprise, the data appeared isotropic, coming equally from all directions rather than along the plane of the Milky Way. Either GRBs lay in our immediate neighborhood, or they were not local at all but rather originated billions of light-years away.

The result was both thrilling and disorienting. If GRBs came from distant galaxies, whatever produced them had to be cataclysmic—some process that could release in seconds as much energy as the sun emits over its entire lifetime.

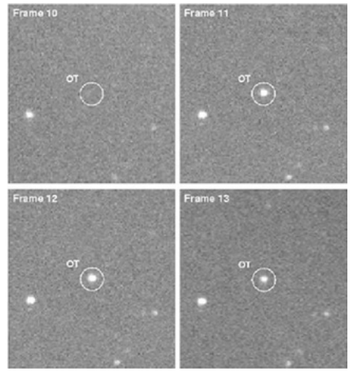
"WE FOUND SOMETHING BECAUSE OF OUR NATIONAL-SECURITY WORK. AND FROM THAT, WE DEVELOPED ENTIRE SCIENTIFIC FIELDS."

Around that same time, Los Alamos gamma-ray imaging technology was appearing on international missions, becoming standard equipment on high-energy astronomy satellites. Independently of that work, the next major breakthrough came in 1997, when the Italian–Dutch BeppoSAX mission localized a gamma-ray burst. Optical telescopes zoomed in and captured its fading afterglow, placing it between eight and nine billion light-years away, far beyond the Milky Way. Now, scientists just had to figure out what physical process could unleash enough power to be seen far across the universe.

That answer arrived a few years later. In 2004, to build on the success of Compton, NASA launched the Swift satellite—built with Los Alamos—to catch GRBs in real time. Using software written by Los Alamos physicist Dave Palmer, Swift could detect a burst, analyze it, and pivot its telescope within seconds to capture the fading light.

Meanwhile, the satellite also sent signals and coordinates to a Los Alamos-built robotic telescope at Fenton Hill in the Jemez Mountains. Once received, the telescope would autonomously swing toward alerts from space—a design replicated worldwide—to capture cosmologically transient events. In one 10-minute observation, the telescope at Fenton Hill recorded a star that seemed to appear and vanish, a visual echo of a burst nine billion light-years away.

"Humans have been watching the sky for 50,000 years," Fenimore says. "We never knew that a star could turn on and off in ten minutes."



What looks like a star materializing out of black space is, in fact, the birth of a black hole —captured by the RAPTOR telescope at Los Alamos's Fenton Hill Observatory on August 20, 2005.

By the early 2000s, astronomers finally understood one cause of what the Velas had glimpsed decades earlier—the violent deaths of massive stars giving birth to black holes. Fenimore and others came to believe that GRBs mark the death of massive stars, between 20 and 100 times the sun's mass collapsing into black holes. The process is fast, chaotic, and extraordinarily violent. As the core implodes, jets of plasma—"star guts," Fenimore calls them—shoot out along the star's rotational axis, and it's the gamma-ray bursts released during this process that the Vela satellites detected. Astonishingly, Vela's descendants detect roughly one such event a day. More astonishingly, these events can only be observed when a jet happens to point directly at Earth, implying that thousands more erupt unseen across the cosmos every day.

What began as a mission to monitor high-energy events from space led to a revolution in astrophysics. It also launched the modern space program at Los Alamos. The techniques developed to study GRBs—detector design, real-time data analysis, and satellite integration—became the foundation of a program that now spans everything from planetary exploration to space-weather forecasting.

"We found something because of our national-security work," Fenimore says. "And from that, we developed entire scientific fields that in turn improved our national security. That's what a national laboratory does." ■

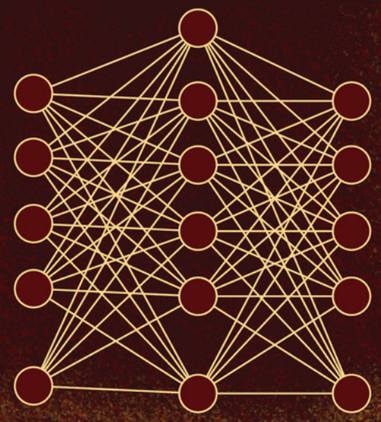
INFORMATION SCIENCE
AND TECHNOLOGY:

POWERING PREDICTIVE DISCOVERY

The ability to predict physical phenomena at scale relies on the fusion of skill, data, and computational power—a fusion Los Alamos has mastered since the time when 'computers' were people, doing complex calculations by hand.

The Laboratory leads advancements in computing, algorithms, and information science that enable predictive modeling of complex systems. Landmark contributions include the invention of the Monte Carlo method, pioneering work in fluid dynamics and materials modeling, and foundational research in chaos theory—beginning with nonlinear wave equations that revealed surprising complexity in simple systems. The Laboratory also revolutionized how science is shared by launching the world's first open-access preprint server, which endures today. From simulating early weapons designs to training the latest artificial intelligence systems, Los Alamos continues to push the boundaries of computational science, developing cutting-edge algorithms and architectures to model everything from turbulence to tumors.

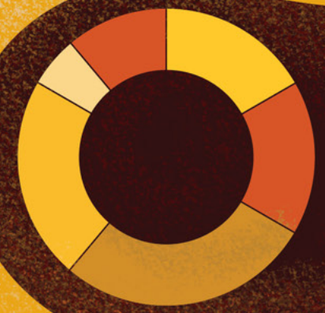




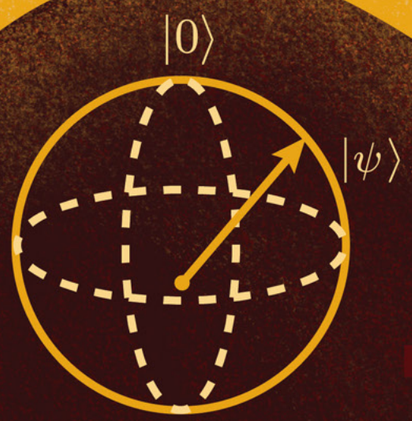
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

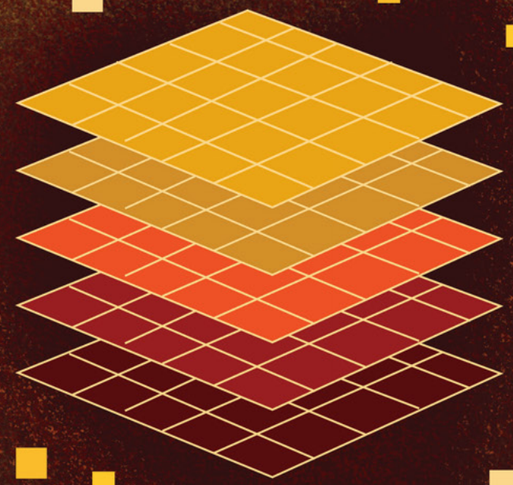
where $|\alpha|^2 + |\beta|^2 = 1$

```
function train(x, y):
  w ← initialize_weights()
  for i in range(N):
    ŷ ← model(x, w)
    L ← loss(y, ŷ)
    g ← ∇w L
    w ← w − ηg
  return w
```





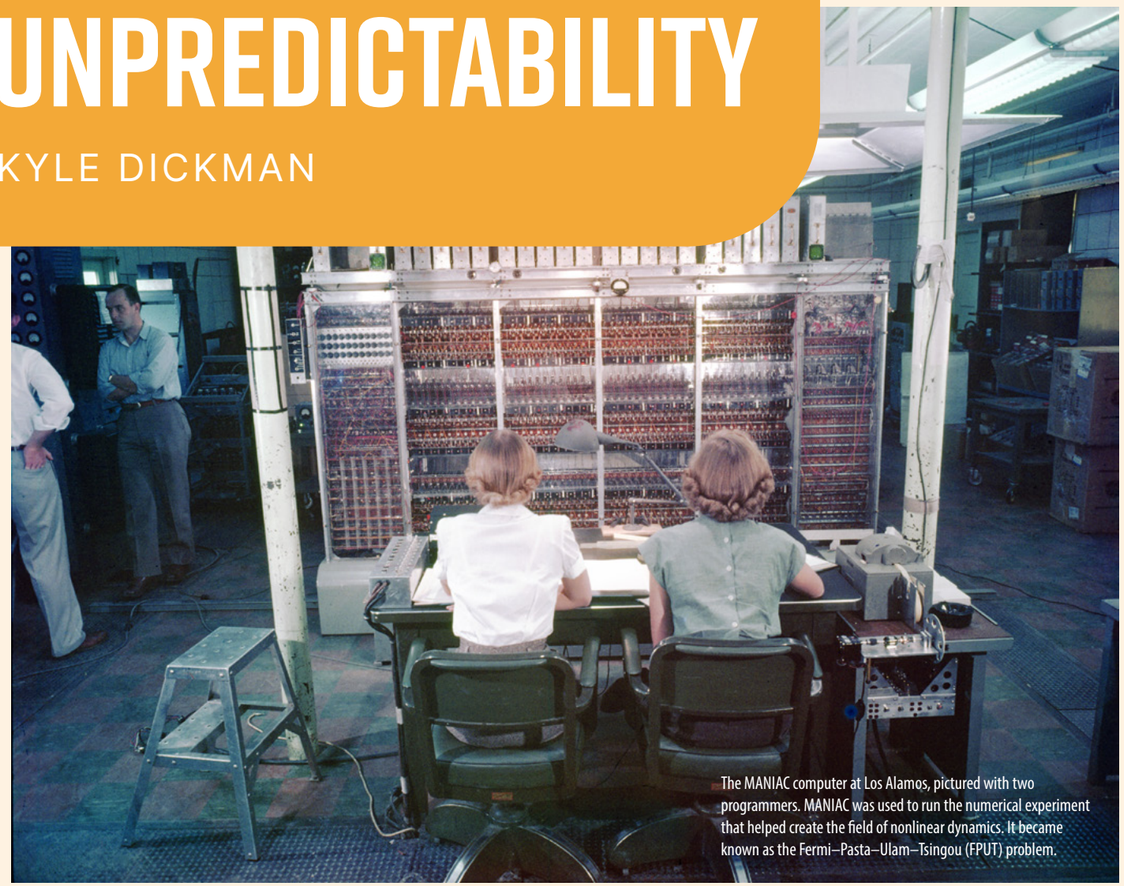






THE SCIENCE OF UNPREDICTABILITY

KYLE DICKMAN



The MANIAC computer at Los Alamos, pictured with two programmers. MANIAC was used to run the numerical experiment that helped create the field of nonlinear dynamics. It became known as the Fermi–Pasta–Ulam–Tsingou (FPUT) problem.

A Nobel laureate, a brilliant programmer, and two unexpected discoveries—the rise of nonlinear dynamics at Los Alamos.

In 1955, 26-year-old mathematician and programmer Mary Tsingou sat in a cool, windowless room in a Los Alamos technical area before a wall of droning electronics: MANIAC. One of the world's first scientific computers, MANIAC hummed, blinked, and hammered out rows of numbers on a mechanical printer. Tsingou had written code for a first-of-its-kind numerical experiment—now known as the Fermi–Pasta–Ulam–Tsingou, or FPUT problem. Conceived years earlier by Enrico Fermi, John Pasta, and Stanislaw Ulam, the experiment would uncover a paradox that would reshape how scientists think about systems as varied as the atmosphere, fusion plasmas, the economy, and even the rhythms of the human heart.

"Fermi passed away in 1954 and never saw the full paradox his idea would uncover," says Avadh Saxena, a physicist and Lab Fellow who studies nonlinear phenomena at Los Alamos. "But the results were a watershed moment. They showed that nonlinear systems behave in surprisingly stable and structured ways, even when intuition says they should fall apart." The simulation Tsingou coded and ran over a few years was a one-dimensional line of masses connected by springs, but Fermi added a small non-linear change to the spring force. Simple, yet it captured the nonlinear interactions of atoms, a system too small for experiments to observe directly. Fermi had designed the model to probe a fundamental assumption among physicists at the time—that even if a system wasn't perfectly linear, energy should still spread out and thermalize much the same way it does in linear systems. The thinking went that small nonlinearities wouldn't change how energy flows. To test that assumption, Fermi introduced a small nonlinear term into the springs' restoring force. By hand, Tsingou wrote out the code and algorithm to simulate the problem on MANIAC.



Mary Tsingou, around the time she wrote the code for the Fermi–Pasta–Ulam–Tsingou (FPUT) problem.

"We made flowcharts," recalled Tsingou in later interviews. She is now in her nineties and still lives in Los Alamos. "Because when you're debugging a problem, you want to know where you are so you can stop at different places and look at things. Like any project, you have some idea, but as you go along, you have to make adjustments and corrections, or you have to back up and try a different approach."

Running the simulation unfolded over years. But on that winter day, as Tsingou watched the machine clacking out the results, she saw that the energy initially spread into other modes—just as Fermi and his coauthors had expected. But then something extraordinary happened. Energy flowed back, almost perfectly, into the mode where it had started. It was as if the system remembered its initial state and returned to it. Instead of drifting inexorably toward equilibrium, Tsingou and her collaborators had demonstrated—numerically, and for the first time—that the natural world does not always behave according to the tidy expectations of linear dynamics. Nature is messy.

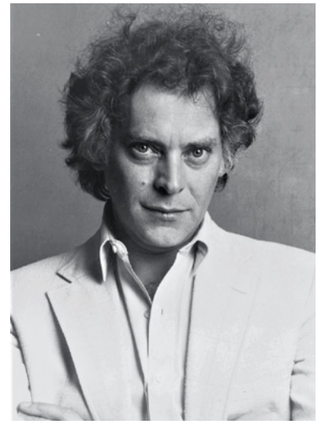
To appreciate the magnitude of this result, a refresher on what "linear" means is a good place to start. In a linear system, causes and effects scale proportionally: double the force, double the response. Such systems are orderly, predictable, and mathematically tractable. Our engineered world depends on linear relationships that explain how things like arches, bridges, and walls hold firm. But much of nature doesn't play by these rules. In certain natural systems, energy not only fails to disperse evenly; it can be trapped, amplified, or assembled into coherent structures that arise out of apparent disorder.

One shining example of how discoveries unearthed by FPUT molded the modern world is solitons, stable packets of energy that travel without dispersing. Understanding solitons proved essential to the development of long-distance optical fiber communications, which depend on pulses of light that carry information across continents. Put more simply: it was essential for creating the internet.

Beyond eventually tangible technologies, the FPUT experiment revealed the power of simulation as a new kind of scientific tool, one capable of uncovering physical behavior that neither hand calculation nor experiments could reach. But it also forced science to reckon with a world where prediction, stability, and control look very different than what linear dynamics proposed. "Once you move beyond the simplest interactions, everything becomes emergent, coupled, and sensitive," Saxena says. "Tiny nudges can have enormous consequences."

CHAOS, IN THE SCIENTIFIC SENSE, ISN'T RANDOMNESS OR DISORDER. IT IS DETERMINISTIC UNPREDICTABILITY.

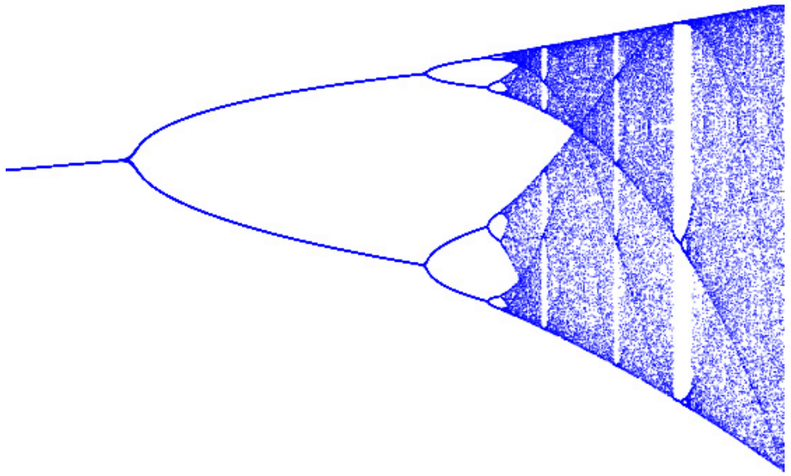
Two decades later, in the mid-1970s, came the Lab's second major contribution to nonlinear science. That's when a young theorist named Mitchell Feigenbaum left Virginia for Los Alamos. Soon after arriving, Feigenbaum began picking apart another nonlinear system, one that described how the state of a system at one moment determines its state in the next.



Mitchell Feigenbaum, photographed years after his Los Alamos work, whose discovery of universal constants revealed how nonlinear systems transition to chaos.

Feigenbaum was interested in systems governed by feedback, where outputs feed back into inputs. Such models appear everywhere, from population dynamics to electrical circuits. His questions were fundamental: when does orderly behavior break down, and how does regularity give way to irregular, unpredictable behavior? Is the transition smooth, or does it follow a deeper pattern? Famously too impatient to wait for time on the Lab's supercomputers, Feigenbaum chased his intuition about chaos with a pencil and a programmable calculator.

Chaos, in the scientific sense, isn't randomness or disorder. It is deterministic unpredictability. As



Read from left to right, this bifurcation diagram shows how a simple system transitions from order to chaos. Regular behavior splits through repeated doubling until the diagram dissolves into a dense cloud of points, each representing a possible outcome sensitive to minute changes in conditions. The pattern reveals that chaos is not disorder, but structured, deterministic unpredictability.

many nonlinear systems are pushed harder, they don't slide smoothly into chaos. Instead, their regular behavior fractures in stages. The process, called period doubling, describes how a system that once repeated every cycle begins oscillating between two repeating states, then four, then eight, and so on. Feigenbaum noticed that each successive doubling occurred after a change in conditions about 4.67 times smaller than the one before it. Practically speaking, this meant that in short order, infinite bifurcations were squeezed into a finite range of conditions, making long-term prediction impossible. "I called my parents that evening and told them that I had discovered something truly remarkable that, when I had understood it, would make me a famous man," Feigenbaum later recalled. He did indeed become famous in certain scientific circles. "The behavior of a wide class of nonlinear systems was governed by the same numbers." From tornado formation to dripping faucets, Feigenbaum had uncovered a universal rule that governs how systems march toward chaos.

"ONCE YOU RECOGNIZE THE MATHEMATICS, THE CONNECTIONS BECOME OBVIOUS. EVERYTHING IS CONNECTED."

By 1980, Los Alamos was well known for its contribution to the field of nonlinear dynamics and founded the Center for Nonlinear Studies, the first institute of its kind. In the decades since, researchers there have shown that the same nonlinear mathematics appear in shockwave propagation, material failure, ocean-atmosphere coupling, earthquake rupture, and astrophysical explosions. "Once you recognize the mathematics," Saxena says, "the connections become obvious. Everything is connected."

Saxena and others are applying nonlinear ideas back to the field's computational roots through studies of quantum materials. Their work focuses on designing topological materials that could enable new kinds of quantum conductors, sensors, and diagnostics—tools that could push computational science beyond the limits of classical models. If realized, these materials could form the basis of quantum computers designed to tackle problems classical computers struggle to represent at all, like the complex nonlinear systems that Fermi, Pasta, Ulam, and Tsingou first wrestled with 70 years ago.

"Human creativity, intuition, and the scientific process remain our best tools for applying nonlinear ideas to the most complex problems we face," says Saxena. ■

BIG CHANGE FOR INFORMATION EXCHANGE

ELEANOR HUTTERER



A visualization of arXiv's complex network, showing how the platform connects researchers across fields.

The archive that rewired research and launched a revolution.

IN 1991, LOS ALAMOS PHYSICIST Paul Ginsparg had a problem with how research findings were shared, or not, within the scientific community. New findings were slow to publish, and access was exclusive, hindering creativity and collaboration. And he wasn't alone; it was increasingly apparent that physicists needed a faster and more equitable way to share results.

"There was something unfair about a system where there was a privileged loop where people in the know were passing around this information and benefiting from it, whereas people out of this privileged loop, at second tier institutions or abroad, were not able to benefit from these communication channels," Ginsparg recalls.

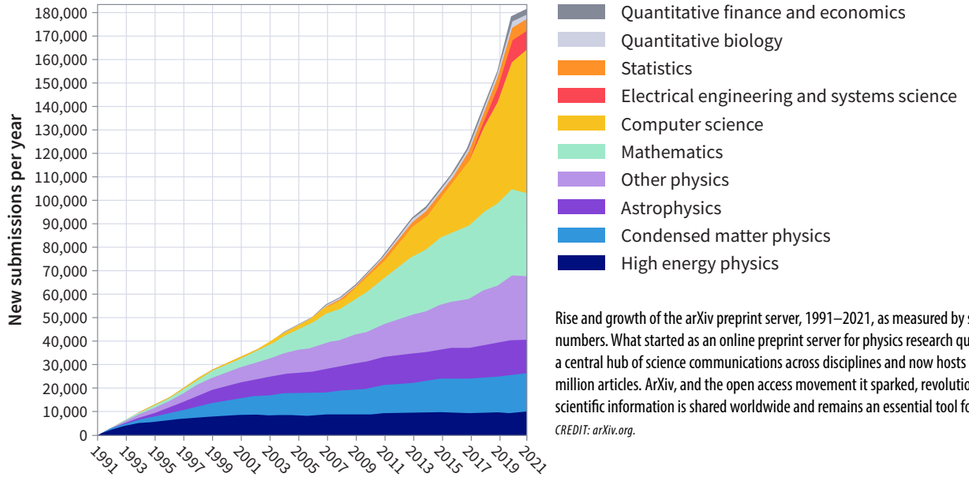
The internet existed but it was not yet the infrastructure of civilization that it is today; it was a tool for specialists, a network of networks connecting researchers in academia, industry, and government. Its users were people who knew how to use command-line interfaces, mainly scientists, engineers, and computer hobbyists. Research results were shared via email mailing list, then downloaded.

"Disc space on accounts was very limited," says Ginsparg, "so it became natural to think about having some kind of central repository." He was an early adapter of the internet and saw in it an opportunity to create a research-sharing platform that would revolutionize scientific discourse.

At Los Alamos, he built and launched the world's first scientific preprint server, a place on the internet where people could share their work without waiting for the slow and formal process of journal publication. Researchers still needed to publish in journals, but the preprint server let them share their completed manuscripts with colleagues, keeping new ideas moving and fostering collaboration, while waiting for the journal to perform the due diligence known as peer review. Ginsparg called it the "LANL preprint archive," and he expected one submission every three days or so. In the first six months, it got closer to three submissions per day, and what began as a workaround for slow publishing became the foundation of a new paradigm: knowledge as a shared, global resource.

Today it's called "arXiv" (pronounced "archive") and has received 2.8 million submissions over the past 34 years, which averages to 230 a day. Though no longer housed at Los Alamos (the server and Ginsparg moved to Cornell University in 2001), arXiv now hosts a range of scientific topics and remains the central hub for preprint sharing, particularly in physics and mathematics.

The immediate popularity of arXiv proved that scientists were willing to share openly with



Rise and growth of the arXiv preprint server, 1991–2021, as measured by submission numbers. What started as an online preprint server for physics research quickly became a central hub of science communications across disciplines and now hosts over 2.8 million articles. ArXiv, and the open access movement it sparked, revolutionized how scientific information is shared worldwide and remains an essential tool for discovery.
CREDIT: arXiv.org.

one another and that self-archiving could work on a global scale. By the late 1990s, there were other online archives popping up, and the open access movement was growing. But each new repository used its own database structure and metadata format, so users couldn't easily search across them or aggregate their contents. There needed to be some standardization, so in 2001, leaders from arXiv along with several likeminded colleagues launched the Open Archives Initiative (OAI), with the objective of defining a simple, universal protocol that any archive could use to manage metadata in a standardized way, thus making all the new digital repositories interoperable.

The OAI's Protocol for Metadata Harvesting (OAI-PMH) became the standard for the open access movement and still runs under the hood of most modern repositories and open science archives. Even as newer technologies slowly replace the OAI-PMH, its legacy persists in the baked-in assumption that metadata should be openly exchanged.

"This is a great example of the Lab's role in discovery," says Bill Priedhorsky, retired Los Alamos physicist and Laboratory Fellow. "The Laboratory starts a lot of things, but we don't necessarily finish them—that's not our job. Los Alamos scientists explore the frontiers of their fields, get big new ideas started, then hand things off once they're tractable."

ArXiv democratized access to research results and accelerated scholarly communication, sparking the open access movement. What sets arXiv apart is that it's preprint—straight from the researcher to the scientific community, with formal publication to follow. Submissions are vetted by moderators to ensure they meet a minimum standard but are not evaluated for correctness or scientific rigor. Users accept the mutability of preprint in exchange for speed and transparency.

Many major discoveries from across the sciences first appeared on arXiv. Examples include "Attention Is All You Need," the paper that launched AI into the public consciousness; and "Observation of Gravitational Waves from a Binary Black Hole Merger," the paper that announced the first ever observation of ripples in spacetime that Einstein predicted a century earlier. And in time-sensitive scientific circumstances, like the start of the COVID-19 pandemic, when new information was arriving each day, the immediacy of preprint far outstrips the polish of peer review.

"WHAT BEGAN AS A WORKAROUND FOR SLOW PUBLISHING BECAME THE FOUNDATION OF A NEW PARADIGM: KNOWLEDGE AS A SHARED, GLOBAL RESOURCE."

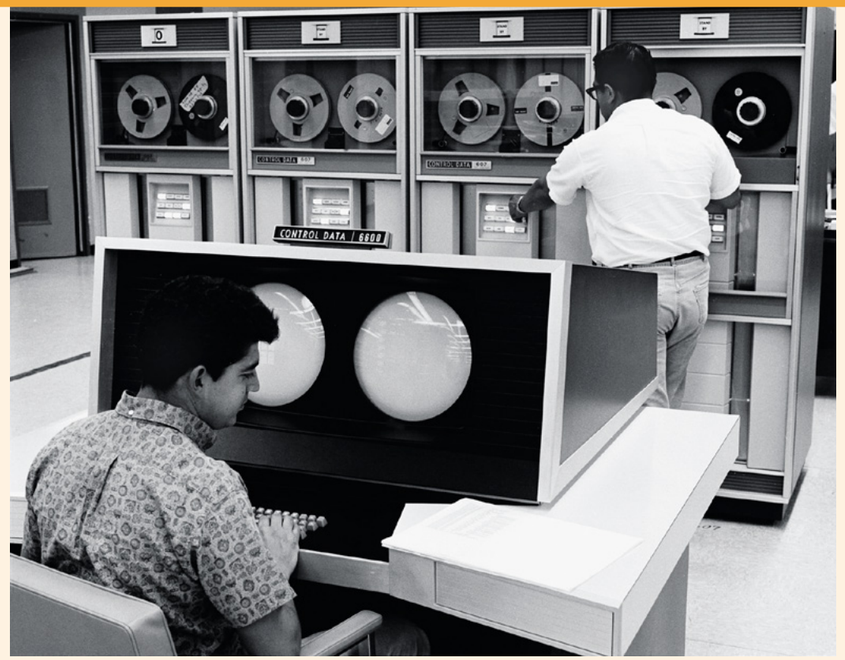
Today's internet is rife with archives and repositories, some doing similar jobs to arXiv, but none are doing it better. It's the original. Strong and simple and standing the tests of time, it's the cast iron skillet of scientific communication platforms—there are newer flashier versions, but the original remains the favorite. It's the first place many researchers go when seeking new information.

"It just grew and grew and took over the world," says Priedhorsky. "It's the one archive that rules them all." ■

FROM MONTE CARLO TO EXASCALE

ELEANOR HUTTERER

How Los Alamos built the algorithms that changed science and defined an era.

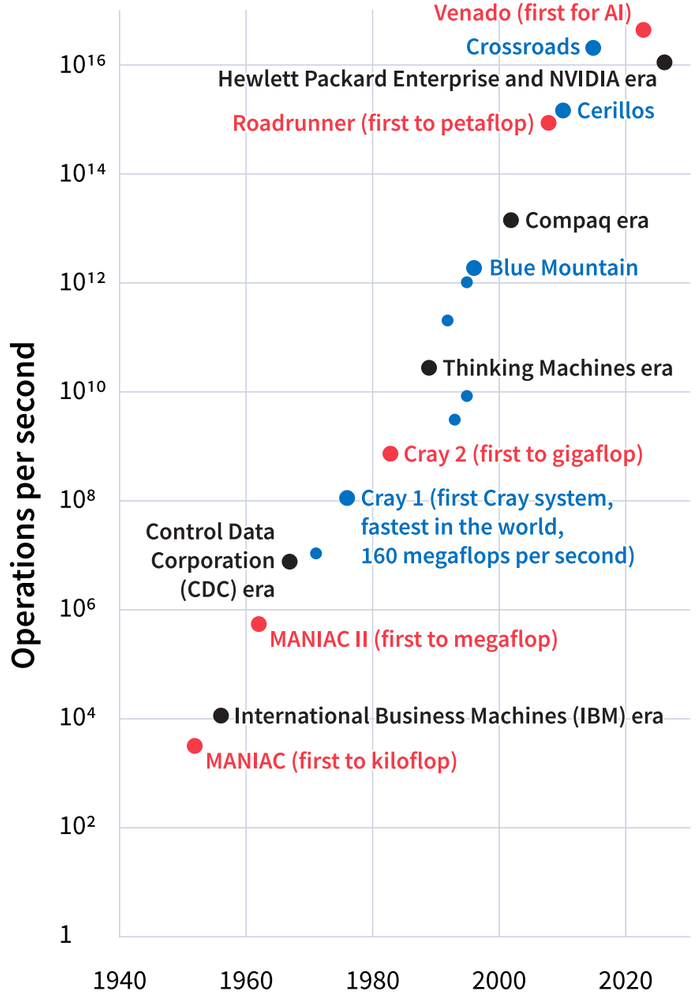


The CDC 6600 system was released in 1964 and is widely considered to be the world's first supercomputer. The Lab had four of them, making Los Alamos one of the first sites on Earth to compute large-scale numerical simulation on a true supercomputer.

"AT THE TIME OF THE Manhattan Project we could barely calculate a basic one-dimensional model of an implosion," says Bill Priedhorsky, retired Los Alamos physicist and Laboratory Fellow. "The key questions were: Is it going to implode or come apart? Will it stay together long enough to get any nuclear yield?" These were incredibly hard questions, never before calculated, and the computers that Laboratory scientists relied on for answers to these questions were humans, doing the calculations by hand with mechanical calculators.

Today, the newest supercomputers at Los Alamos are Crossroads and Venado, which both perform on the petaflop scale (1015 operations per second). Advancing from mechanical calculators doing less than one operation per second to petaflop supercomputers is more than a 50 percent increase in computational power every year, compounded continuously for eight decades—which is staggering. But computing power is only as useful as the algorithms it drives. Here, too, Los Alamos has compounded continual growth.

The problems that the Laboratory tackles today—from modernizing the nuclear stockpile to modeling the Universe at its largest and smallest scales—involve the predictive modeling of complex systems. These kinds of models need sophisticated algorithms, usually custom built to address a specific question. The algorithms in turn require ever increasing raw computing power. For over 80 years, the scientific progress of Los Alamos has been driven by the interplay of problem complexity, algorithmic sophistication, and computing power, as each new challenge demands more advanced methods and the machines to meet it.



Los Alamos tackles problems that demand complex simulations, driving ever more advanced algorithms and computing power in a cycle of mutual advancement spanning more than 80 years. From the very first electronic computer at the Lab, called MANIAC (Mathematical Analyzer, Numerical Integrator, and Computer), to today's petaflop supercomputer, called Venado and optimized for AI, Los Alamos has continually pushed the limits of computing power. Here, black dots denote key industry partners by era, red dots denote specific processing milestones, and blue dots are other notable computing systems at Los Alamos.

Monte Carlo Methods

Los Alamos led the way in applied algorithm development starting with the Monte Carlo method, first explored by Los Alamos physicist and mathematician Stanislaw Ulam in 1946. Ulam's Monte Carlo method, named for the famous casino in Monaco, is a mathematical approach that uses repeated random sampling to model certain complex phenomena. Ulam devised it while thinking about a card game, but he and his Los Alamos colleagues quickly saw its utility for problems describing neutron diffusion within a nuclear weapon.

Through the 1950s and 1960s, the Lab's fleet of fledgling electronic computers reached 10^4, then 10^6 operations per second. In parallel, a suite of Monte Carlo spinoff methods was written into codes for these computers to model increasingly complex neutron and photon transport problems. Chief among these descendants is the Metropolis algorithm, published in 1953, for sampling from complex probability distributions, and the general-purpose Monte Carlo N-Particle (MCNP) transport code, which Los Alamos scientists devised in 1977 and released to the public in 1983.

The Metropolis algorithm and MCNP, as well as other progeny of the original Monte Carlo method, are still widely used today in science, engineering, and even game theory. These algorithms have enormous influence in computation and machine learning methods and collectively comprise one of the most prominent and longest lasting algorithmic contributions by Los Alamos scientists.

The PARTISN (Parallel, Time-Dependent S_N) code is another computational tool developed at Los Alamos and now used globally for a variety of applications. As computing power increased through the 1980s—advancing from about 10^8 to 10^{10} operations per second—new three-dimensional and time-dependent algorithms were developed and eventually unified into PARTISN. The tool was developed for the same type of particle transport questions as MCNP, but comes at the problem from a different angle: whereas MCNP is stochastic—stand in a room and throw a billion pieces of confetti, then watch where each piece lands and average the results—PARTISN is deterministic—predict and map the average density of confetti across the whole room at once. They are complementary approaches that, when used together for cross-verification, yield a more detailed result than either code can alone.

FOR OVER 80 YEARS, THE SCIENTIFIC PROGRESS OF LOS ALAMOS HAS BEEN DRIVEN BY THE INTERPLAY OF PROBLEM COMPLEXITY, ALGORITHMIC SOPHISTICATION, AND COMPUTING POWER.

Multiscale Modeling

All of the solid materials that make up a nuclear weapon quickly turn into gas and plasma during detonation, so all but the earliest stages of detonation must be modeled as fluids. Los Alamos algorithms again led the way. Robert Richtmyer and Frank Harlow built much of the foundation for the field of computational fluid dynamics during their time at the Lab. Richtmyer led the Theoretical division in the late 1940s and early 1950s. He helped get Monte Carlo going on 1950s computers for particle transport questions, while at the same time pioneering algorithms for shock wave and fluid dynamics problems. Richtmyer's theory of shock instabilities and turbulence lies at the heart of simulations of systems relevant to the modern Laboratory mission, like inertial confinement fusion.

Harlow, a theoretical physicist at the Lab in the 1950s, advanced Richtmyer's ideas by creating innovative numerical techniques that allowed complex fluid flows, turbulence, and instabilities to be simulated computationally for the first time. This work, in conjunction with continual gains in computing power, moved fluid dynamics from the theoretical realm to one of large-scale computer modeling, driving major advances in weapons modeling capabilities, and later to simulations in astrophysics, plasma physics, and engineering.

From fluid dynamics, which applies to liquids, gases, and plasmas, Richtmyer focused in on hydrodynamics, which is specific to noncompressible liquids like water. He and Los Alamos luminaries John von Neumann and Rudolf Peierls created hydrodynamics models based on Lagrangian methods, which observe a fluid's motion by following individual fluid units as they move through space and time. These methods, useful for studying interfaces and deformations, remain central to the Laboratory's simulations in shock physics, hydrodynamic implosion, and plasma physics. In the 1970s, Lab scientists merged Lagrangian methods with Eulerian methods, which use a fixed observation point to watch fluid flow by, producing a powerful hybrid approach to hydrodynamics computation called ALE (Arbitrary Lagrangian-Eulerian) techniques.

In the 1990s, as Lab computers approached 10^{12} operations per second, Los Alamos scientist Arthur Voter developed Accelerated Molecular Dynamics (AMD) methods. Molecular dynamics describes the movements of atoms and molecules based on Isaac Newton's laws of motion. But certain phenomena, like crystal rearrangement in fast-moving materials or radiation damage effects, occur very slowly from the point of view of a molecule in motion. Voter's idea was to make state changes occur more rapidly in a simulation while preserving the correct kinetics. Voter's AMD algorithms accelerated molecular dynamics simulations by orders of magnitude and remain an area of active development at Los Alamos.

Problem complexity, algorithmic novelty, and computing capacity at the Lab have advanced tremendously through mutual synergy, and all three continue to evolve together. The pursuit of ever more complex problems demands more sophisticated algorithms and computational platforms to solve them. Likewise, innovation in algorithm design and high-performance computing architectures expands the frontier of what questions can even be asked. This dynamic cycle—where complexity drives computation, computation drives insight, and insight feeds new complexity—is key to the Laboratory's legacy of discovery. ■



MATERIALS FOR THE FUTURE:

CONTROLLING PERFORMANCE AT EVERY SCALE

Materials science at Los Alamos is rooted in predicting, controlling, and refining materials' performance. The Lab's materials science expertise underpins its ability to certify the nation's nuclear stockpile and address other scientific national security challenges.

From Manhattan Project–era work pioneering plutonium metallurgy to today's pursuit of quantum nanomaterials, Los Alamos has consistently led the field of advanced materials for basic and applied science. From prototype to production, Los Alamos scientists design alloys and compounds that deliver predictable performance in extreme environments. Examples include specialized plutonium alloys, plastic-bonded explosives, and nanomaterials with tailorable optical and electronic properties. Los Alamos helped launch the field of nanomaterials, enabling technologies like quantum dot displays, advanced sensors, and metamaterials to control light and sound. At Los Alamos, quantum behavior is not only observed but engineered, and Lab research on quantum-dominated materials is laying the foundation for future quantum hardware.



The Lab's main machine shop, circa 1955. The Laboratory's onsite prototype fabrication capability has always been key to rapid integration of data and design.

MANUFACTURING THE MISSION

ELEANOR HUTTERER

Los Alamos doesn't just design materials and weapons systems—it invents how to make them.

A ROBOTIC ARM INSIDE A GLOVEBOX deftly removes surface impurities from a plutonium part, while in another facility, a high-output laser cutter slices inch-thick metal with micron-precision. 3D printers create parts out of glass and ceramics, while ion beam etchers imprint intricate designs smaller than the width of a human hair. All this technology is working toward a single mission: ensuring the effectiveness of America's nuclear deterrent through nuclear weapons design, certification, and component manufacturing. Across Los Alamos, scientists and engineers develop and deploy advanced manufacturing methods to achieve excellence not only in what gets made, but in how it gets made.

From prototype to production, manufacturing at Los Alamos is a scientific discipline in its own right. As the Laboratory that conceived the nation's most complex deterrence systems, Los Alamos also invented the materials, processes, and production methods required to build them. Manufacturing here has always been more than fabrication. Even in the 1940s—when custom parts were shaped and tooled by hand—manufacturing was a deliberate fusion of science, engineering, and national security. Through alloy development, explosives formulation, and manufacturing science, Lab researchers have been linking materials behavior to performance, transforming theory into deterrence for more than 80 years.

Manufacturing under pressure

The original mission of wartime Los Alamos was to invent and produce the world's first atomic weapons, and to do it fast, with no playbook and no prior industry. Nuclear fission had been discovered just a few years earlier, yet Lab scientists and engineers now needed to master two fissile materials: plutonium and uranium. The task was not only to quickly come up with designs that would work, but also to build them repeatedly, reliably, and safely. Scientists and machinists worked hand in hand, pioneering complex processes under wartime pressure. Chemists purified the metals, machinists worked them into the right shapes, and physicists controlled the fission, all with exquisite precision.

The Lab's mission hinged on the taming of plutonium, a human-made metal that resisted domestication at every turn. As well as being highly radioactive, plutonium is brittle at room temperature and ductile at elevated temperatures, meaning freshly made parts would change density and crack as they cooled. Plutonium was so difficult and dangerous to work with that a whole new field of metallurgy was established for it. First, scientists needed to stabilize plutonium into a workable alloy that would retain the necessary nuclear properties while holding its shape, so a slew of alloy candidates were evaluated. Then, they had to melt, cast, and precision-machine the metal into exacting forms, so new fabrication and joining techniques were developed. At the same time, to conserve every gram of the scarce, human-made element, new purification and recovery processes were also pioneered.

Meanwhile, uranium use was also pushing new science. Scientists and engineers had to separate uranium isotopes—and they had to do it at industrial scale and within a compressed timeline. Because isotopes are chemically identical and differ only slightly in mass, conventional chemistry wouldn't work. Instead, new physical separation methods were developed, each of which came with a cost that threatened to outweigh its usefulness: enormous electricity demands, the need to handle highly corrosive chemicals, and the construction of sprawling, purpose-built facilities.

Other manufacturing efforts, beyond fissile material production, were also vital to success. Precise high-explosive components for the nuclear assemblies—detonators, firing systems, custom diagnostic electronics, and the high-explosives themselves—were all developed and fabricated at Los Alamos. Many still are.

Manufacturing comes of age

After the war, manufacturing at Los Alamos matured from wartime improvisation into an integrated scientific discipline to tackle increasingly complex national security challenges and to power national-scale production. A variety of additional plutonium and uranium alloys were developed during this time, each with tailored properties for specific nuclear applications, and manufacturing methods evolved too.

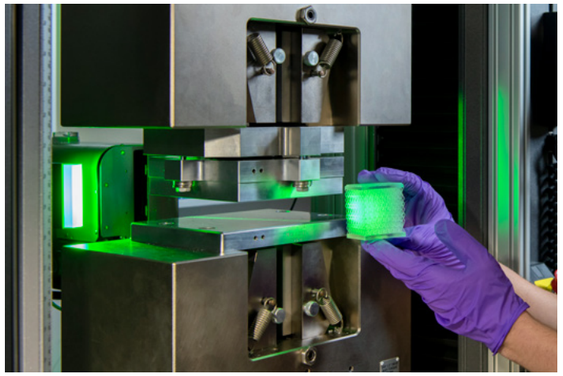
FROM PROTOTYPE TO PRODUCTION, MANUFACTURING AT LOS ALAMOS IS A SCIENTIFIC DISCIPLINE IN ITS OWN RIGHT.

Traditional casting of uranium involved melting the metal, pouring it into graphite molds, then machining the cooled part into its final form. It was slow and labor intensive. In the late 1940s, wrought processing—mechanical shaping through rolling, extruding, and forging—came into play and became the preferred method because it offered higher throughput and fidelity. But wrought processing isn't very versatile, so, in the early 2000s, Los Alamos metallurgists reimagined uranium casting again. Aiming to improve manufacturing agility, they developed a new method called direct casting. Enabled by vastly improved graphite molds—themselves a manufacturing feat—direct casting produces near-final shape components, drastically cutting post-casting

A robotic arm inside a demonstration glovebox, similar to those where plutonium parts for nuclear weapons are handled, can help reduce human radiation exposure.



This high-precision laser cutter has improved production speed for precision cut metal pieces by fifty-fold.



Advanced 3D printing can produce items with elaborate internal architectures that were previously impossible.

machining time. It's more agile because now, if the design for a particular piece needs to change, it's done by changing the mold, rather than an entire tooling suite.

High explosives too have been diversified and specialized. For example, in the 1950s, Los Alamos invented a plastic-bonded conventional high explosive called PBX 9501, which was safer for handling and transportation compared to previous generations of explosives. By binding explosive powder with a synthetic polymer, the explosive material was made less sensitive to physical shocks and temperature fluctuation, making it easier to machine without compromising performance. In the 1960s, Los Alamos formulated PBX 9502, the first insensitive high explosive to be developed for nuclear weapons. The motivation again was safety—"insensitive" high explosives need very particular initiation conditions and won't accidentally detonate in cases of fire, impact, or bullet strike.



A suite of logos etched onto silicon by a focused ion beam. Each logo is just 100 microns across, roughly the same width as a human hair.
CREDIT: Ben Morrow

Underpinning the development of novel materials is a deep understanding of how they behave under extreme conditions. At Los Alamos, dynamic experiments expose metals and explosives to high pressures and temperatures, revealing how they respond. The resulting data enable rapid iteration of new parts. Key to this integration of data and design is the Lab's in-house prototype fabrication capability. Thousands of prototype components are designed, built, evaluated, and refined each year, tightly coupling experiment and production to shorten timelines and reduce risks.

Modern manufacturing

Manufacturing remains mission-critical science. As the Lab modernizes the nation's nuclear stockpile, it is once again reinventing how manufacturing is done, leveraging advanced technologies at every turn. Automation, such as robotic arms in gloveboxes, reduces worker exposure to hazards. Additive manufacturing, including advanced 3D printing, enables intricate geometries that were previously impossible. Lasers and real-time metrology are integrated into machining processes, boosting precision and efficiency.

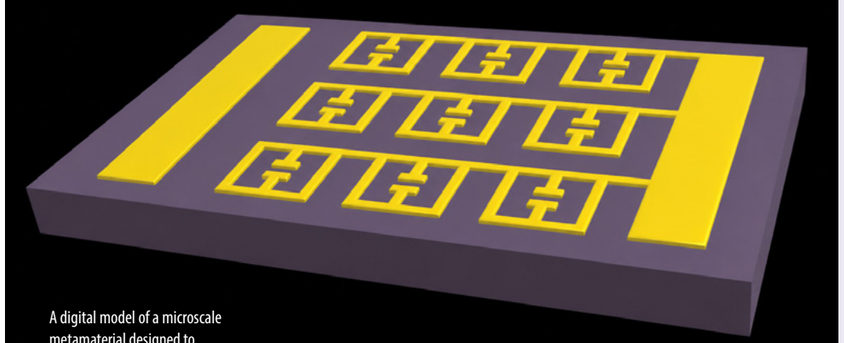
MANUFACTURING REMAINS MISSION-CRITICAL SCIENCE.

Scientists at Los Alamos use high-performance computing to run simulations grounded in physics, mathematics, and decades of experimental research, integrating vast amounts of data to predict materials performance and guide design. Experiments, models, and simulations are developed and interpreted in tandem, with researchers continuously refining each. Emerging artificial intelligence tools, coupled with these computational capabilities, can accelerate this process—helping scientists design new metal alloys, develop chemical separation methods, identify promising explosive molecules, and detect defects in production processes so they can be evaluated and controlled.

Today manufacturing is no longer downstream of design; it is embedded in the process from the outset, accelerating results while reducing uncertainty. For more than 80 years, the Lab's enduring strength has been not only its ability to imagine what must be built—but also to invent how to build it. As national security demands evolve, that fusion of materials science, experimentation, and production will remain essential. ■

DESIGNING MATTER AT THE NANOSCALE

KYLE DICKMAN



A digital model of a microscale metamaterial designed to control light waves.

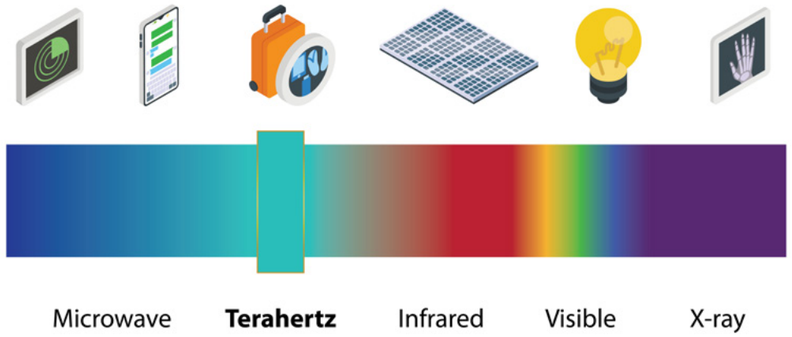
How the Center for Integrated Nanotechnologies helps Los Alamos scientists transform theory into working materials.

"We didn't have modulators," Toni Taylor, a Los Alamos National Laboratory Fellow and physicist, says matter-of-factly, recalling work she began nearly two decades ago at the Center for Integrated Nanotechnologies (CINT) in Los Alamos. Modulators are the devices that allow scientists to control light—shaping its amplitude, phase, or frequency so it can carry information. Without modulators, terahertz light, a band of frequencies with enormous potential for communications and medical applications, could not reliably carry information. Without modulators, terahertz stubbornly remained one of the last regions of the electromagnetic spectrum to be technologically mastered.

Too slow for optics, too fast for electronics—the terahertz band lies between microwaves and infrared light, a narrow stretch of the electromagnetic spectrum wedged between two frequency regimes that have powered technological innovation for decades. In the 1940s, engineers developed radar by mastering microwaves with electronic circuits that could modulate the signals, and by the latter half of the twentieth century, physicists had built photonic devices to do the same with infrared and visible light for computation and communications. But unlike those light bands, when terahertz radiation hits the materials used to make conventional modulators, the waves mostly pass through: little absorption, little reflection, little control. That limitation became known as the terahertz gap, and it left significant technological potential untapped.

FOR THE FIRST TIME, NANOSCALE ENGINEERING WAS BECOMING PRACTICAL.

Terahertz waves oscillate trillions of times per second, hundreds of times faster than the microwave-frequency systems used in today's wireless networks. In principle, that behavior means they could carry vastly more information than today's fastest consumer networks. But communications is only part of the appeal. Like x-rays, terahertz radiation can penetrate many nonmetallic materials, but unlike x-rays, it doesn't ionize atoms, meaning it



Terahertz radiation lies between microwaves and infrared light—a narrow region once known as the "terahertz gap" because conventional electronic and optical materials could not easily control it. Work at the Center for Integrated Nanotechnologies helped turn that gap from a scientific limitation into an engineering challenge that could be solved.

doesn't change the materials' structure. In theory, that makes terahertz radiation well-suited to nondestructive probing of delicate materials, from biological tissue to concealed explosives. "There just weren't good photonics devices there," Taylor says. "At the time, neither naturally occurring materials nor manmade alloys interacted strongly enough in that band to control it."

By the early 2000s, when Taylor and coworkers began working in the terahertz band, the computer revolution had pushed technology to an inflection point. Moore's Law was still busy shrinking transistors, but devices had reached dimensions small enough that quantum effects shaped performance. Advances could no longer come from simply making components smaller. To keep accelerating computation, materials had to be designed down to the level of their very atoms.

For the first time, nanoscale engineering, working at dimensions of billionths of a meter, where materials behave in fundamentally new ways, was becoming practical. Long before nano products were built, scientists could model them on supercomputers that predicted how electrons and electromagnetic waves would behave in such tiny structures. Cleanroom fabrication techniques refined by the microelectronics industry were building structures smaller than one hundred nanometers with remarkable precision, while scanning tunneling microscopes and atomic force microscopes made it possible not only to image the placements of individual atoms but, in some cases, to nudge them deliberately into place.

THE CENTER FOR INTEGRATED NANOTECHNOLOGIES IS A CENTERPIECE FACILITY AMONG NANOSCALE RESEARCH CENTERS.

All of these technological factors, plus the promise of the capabilities they enabled, led the Department of Energy's Office of Science to create the Center for Integrated Nanotechnologies, a centerpiece facility among a national network of nanoscale research centers. Opened in 2004 and jointly operated by Los Alamos and Sandia national laboratories, CINT was built as a user facility, a place where scientists from around the world could propose ideas and gain access to specialized tools and expertise. Housed within this tightly integrated environment, researchers could move from theory to synthesis to fabrication to characterization—all at the nanoscale.

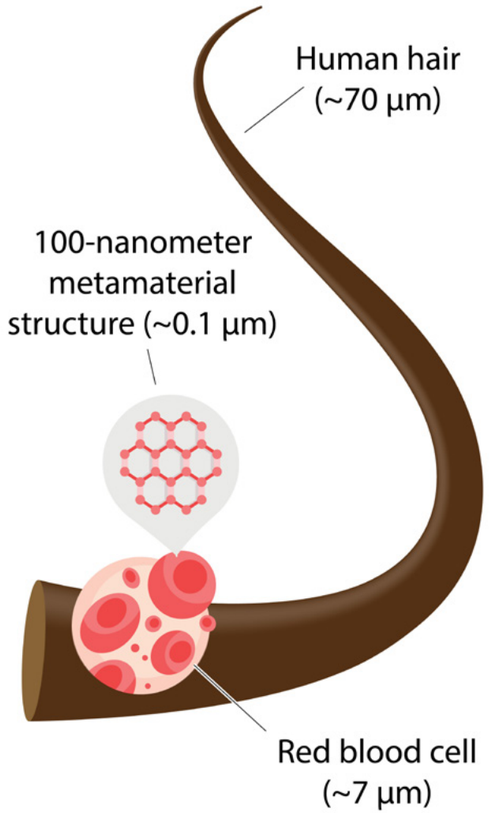
For researchers like Taylor, CINT turned the terahertz gap from an abstract limitation into an engineering problem. "All of the tools needed to develop the modulators were at CINT," Taylor says. Her team's work on the project began in earnest in 2006, when a postdoctoral researcher named Willie Padilla arrived at Los Alamos with expertise in metamaterials: artificially structured surfaces engineered to manipulate electromagnetic waves in ways natural materials cannot.

The way a material traditionally absorbs or reflects light is dictated by its atomic composition—the electronic transitions and vibrational modes built into its chemistry. Padilla's insight was that they no longer had to rely on the electronic structure of naturally occurring materials to support a resonance at terahertz frequencies. They could engineer a material instead.

Using CINT's modeling tools, he and his collaborators designed metallic patterns sized to resonate at terahertz frequencies: tiny, repeating loops and gaps etched into a thin film of gold. When a terahertz wave struck the patterned surface, its oscillating electric field drove the metal's free electrons back and forth. If the geometry was right—if the loops and gaps were sized precisely for that frequency—the electrons would move in sync with the incoming wave. The energy in the terahertz waves that would otherwise have passed quietly through the material was briefly captured, scattered, or absorbed. Like radio antennas tuned to a single station, the gold resonators responded strongly only at the frequency dictated by their shape.

But this was still a passive response, like a filter or detector. The resonator device could isolate or suppress an individual frequency, but couldn't change that frequency in real time. Without time-dependent control, it wasn't yet useful for information transmission. To do that, Padilla, along with his coworkers Hou-Tong Chen, Willie Padilla, Richard Averitt, and Taylor had to find a way to modulate the signal itself.

The solution lay in setting the patterned metal resonator atop a semiconductor substrate. By injecting charge into that substrate—electrically or with an ultrafast optical pulse—the team temporarily increased its conductivity. That shift altered how freely the electrons in the resonators could oscillate. When the substrate became more conductive, the oscillations dissipated energy more quickly and the response weakened; when it was less conductive, the resonance sharpened. In practical terms, a static surface had become a controllable gate. A region of the spectrum long considered technologically awkward could now be modulated in real time. The work culminated in a 2006 paper demonstrating active control of terahertz radiation.



A human hair is about ten red blood cells wide. A red blood cell is roughly seventy times larger than a typical virus. The nanoscale structures engineered at the Center for Integrated Nanotechnologies measure about 100 nanometers across—the same scale as many viruses. Manipulating matter at this scale has enabled advances in terahertz control, quantum dots, and other nanoscale materials with entirely new properties.

What followed was not just a device, but a new way of thinking about matter: that it could be modified at the nanoscale to realize ideas once confined to theory. Taylor's group went on to pursue higher-speed modulators, tunable filters, polarization rotators, and broadband converters. They extended the same nanoscale design principles to problems across national security and optical communications. More recently, collaborators demonstrated structures that can generate and steer terahertz radiation with unprecedented control. That approach has contributed to advances in security imaging seen at airports, materials diagnostics, and next-generation wireless research. Recent experimental terahertz systems achieved data rates exceeding 100 gigabits per second, far beyond typical consumer wireless speeds.

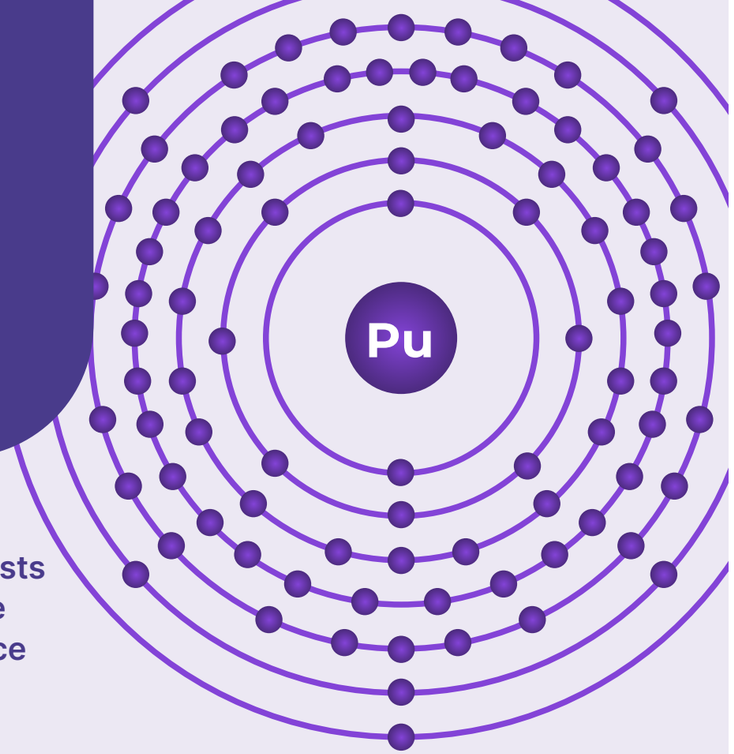
WHAT FOLLOWED WAS A NEW WAY OF THINKING ABOUT MATTER: THAT IT COULD BE MODIFIED AT THE NANOSCALE TO REALIZE IDEAS ONCE CONFINED TO THEORY.

Terahertz modulation is only one expression of CINT's broader vision. Across the Center, researchers have applied the same integration of modeling, fabrication, and measurement to problems ranging from quantum dots to structural materials. Victor Klimov and Jennifer Hollingsworth engineered quantum dots whose optical gain and emission can be tuned with atomic precision, advancing solar technologies, microelectronics, and quantum information science. Other Los Alamos teams designed nanoscale defect architectures to strengthen materials and built atom-scale emitters matched to fiber-optic telecommunications bands. Each effort differs in application, but they share a methodology enabled by CINT: design at the nanoscale, fabricate precisely, measure rigorously, iterate quickly.

"We wanted to understand the materials and then design them to do the thing that we wanted them to do," Taylor says. The science has advanced since the early days of terahertz modulators. The ambition remains the same: to design matter itself. ■

A PHASE OF ITS OWN

ELEANOR HUTTERER



Plutonium's unusual behavior forced early Los Alamos scientists to rethink metallurgy, laying the foundation for plutonium science as it exists today.

THE SMALL METAL BALL WAS FRESHLY CAST and still hot—100 grams of a brand-new, human-created metal that, on paper, should behave like uranium. The technicians who made it set it aside to cool. By the next day it had warped, cracked, and split in two. No one had touched it, yet the plutonium had changed. At Los Alamos, in early January of 1945, this wasn't just an inconvenience, it was a crisis.

For nearly two years, scientists at Los Alamos had been working feverishly on the Lab's mission of producing a plutonium-based atomic bomb. But that wartime race would be won or lost on a single hurdle: the mastery of plutonium.

Virtually nonexistent in nature, plutonium was first synthesized in late 1940 and was the Manhattan Project's first-choice material for an atomic bomb. In mid-1944 the original gun-style weapon design was scrapped because it wouldn't work with plutonium due to high spontaneous fission, and the scope shifted to a more complex implosion-style design. But as Lab scientists desperately tried to work with it, plutonium's weird behavior, defying basic metallurgy and common sense, was slowing progress down.

In the spring of 1945, key pieces of the puzzle finally started coming together, and mere months later, the Lab delivered the first atomic weapon, an implosion-style bomb with plutonium at its heart. The histories of Los Alamos and plutonium have been intertwined ever since—one would truly not exist without the other. In understanding and harnessing this new human-made element whose behavior was so bizarre, the Lab became the world's center for plutonium science. Nearly every foundational discovery in plutonium metallurgy and materials science over the past eight decades was either made at the Lab or motivated by its science.

Discovery

Plutonium has been described as a physicist's dream and an engineer's nightmare because of its superb nuclear properties and confounding physical properties. Compared to uranium, plutonium is more efficient at fission, meaning far less material is needed to achieve a nuclear chain reaction. But it has six different phases, or crystalline forms, that vary in density by up to 25 percent, and modest changes in temperature or pressure can provoke it to go from being as malleable as aluminum to as brittle as glass. Maddeningly, in certain phases it shrinks as temperature increases, the opposite of how most metals behave. These dramatic changes in density as plutonium transforms from one phase to another is why that first 100-gram ball cracked—its volume collapsed suddenly as it cooled into a denser phase.

Because plutonium's nuclear properties are so ideal, Manhattan Project scientists needed to find a way to make it cooperate. The implosion design demanded metal parts that were dimensionally stable with precisely known densities, but as time passed and temperature changed, the plutonium kept quietly rearranging its internal structure. One strategy was to alloy it, to mix in another element that could stabilize it in its most workable phase, the delta phase. And so began The Plutonium Alloy Survey Program, a rapid, systematic search for phase stabilizers.

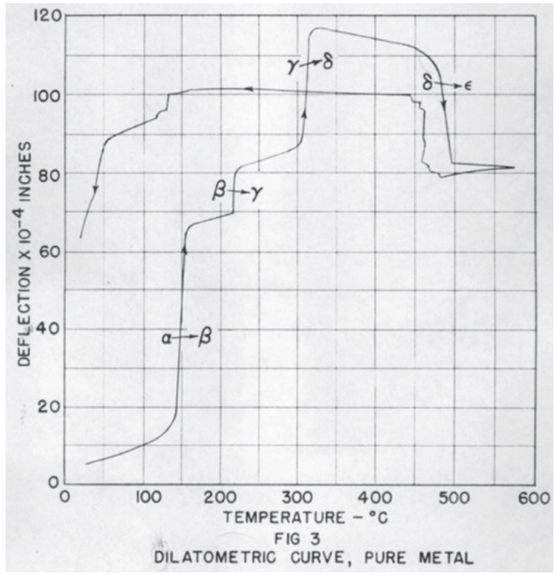
"They threw the kitchen sink at it," says Lab Fellow and retired engineer Joe Martz. "They would combine various elements, up to five at a time, in a little plutonium casting, then look for a density reduction that would indicate the delta phase was stabilized."

Initially they tested about thirty elements. Two of them, silicon and aluminum, showed promising density reduction, so those were pursued further. Aluminum emerged as the frontrunner, creating a beautifully stabilized delta phase plutonium alloy that was easy to machine and didn't crack when it cooled.

Then in March of 1945, the limits on impurity content in plutonium were set, based on prior calculations. They showed that the neutron background that could be tolerated was below what an aluminum alloy would create, meaning to use aluminum would risk pre-detonation or outright fizzle. The best path forward was suddenly and decisively blocked.

"Someone—maybe several scientists discussing—suggested they look at gallium, the element immediately below aluminum on the periodic table," says Martz. "Because of the way the table is organized, gallium shares many chemical and physical characteristics with aluminum."

It was an inspired choice, and within weeks they showed that gallium would make an even better plutonium alloy than aluminum. It was stable, comparatively easy to work with, and crucially, didn't create a large neutron background. Gallium was so good that they ended The Plutonium Alloy Survey Program in April, finalized the implosion-style design in May, and delivered the first plutonium driven atomic bomb in July.



Dilatometry measures how a material's dimensions change with temperature. Here, the first dilatometry curve for unalloyed plutonium, created in 1945, shows five phases: alpha (α), beta (β), gamma (γ), delta (δ), and epsilon (ε). The near-vertical portions indicate where one phase transitions to the next as temperature changes. Later work at Los Alamos on higher-purity plutonium revealed a sixth phase known as delta prime (δ'). *CREDIT: Los Alamos National Laboratory.*

Details

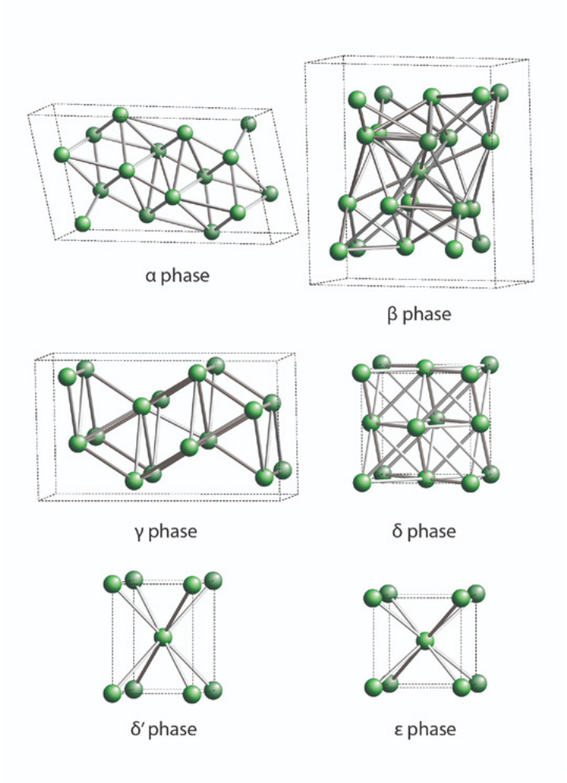
In less than two years the Lab had developed an entirely new metallurgy discipline to take plutonium from barely visible samples to kilogram-scale parts, and that groundwork laid the foundation for all later plutonium science and even the first plutonium-fueled reactor. Post war there were still more questions than answers about the temperamental metal, so Los Alamos scientists moved into more extensive examination.

Lab metallurgists knew that the alpha phase, the form of unalloyed room-temperature plutonium, was dense and brittle but they couldn't explain why. By 1946, innovative x-ray crystallographers had solved the crystal structures for several phases, revealing that in alpha phase, plutonium atoms are locked into a complicated monoclinic structure that doesn't tolerate stress, making it brittle and crack-prone—more like a mineral than an ordinary malleable metal. Delta phase, on the other hand, has a simple cubic crystal structure more typical of most metals.

PLUTONIUM HAS BEEN DESCRIBED AS A PHYSICIST'S DREAM AND AN ENGINEER'S NIGHTMARE BECAUSE OF ITS SUPERB NUCLEAR PROPERTIES AND CONFOUNDING PHYSICAL PROPERTIES.

Also in 1946, the Lab built the Los Alamos Plutonium Fast Reactor, the world's first plutonium-based nuclear reactor. It was nicknamed Clementine after the Gold Rush folk song "Oh My Darling, Clementine," because it was built in a canyon near a cavern and its operators called themselves "49ers", in a wink at plutonium's wartime code name, "49." Built to use metallic plutonium fuel, Clementine was a research tool for studying neutron cross sections, spectra, and high-energy effects. Clementine was designed in the immediate shadow of two fatalities caused by hands-on criticality experiments—Harry Daghlian in 1945 and Louis Slotin in 1946. Because of those tragedies, the reactor incorporated remote-handling safety systems, signaling an important shift in how the Lab approached dangerous work. Over the six years that it was operational, Clementine taught plutonium scientists an enormous amount about neutrons, plutonium, and reactors. Even when it failed—first in 1950 and terminally in 1952—it yielded valuable insights. The reactor was decommissioned when its plutonium metal fuel rods were found to have ruptured due to structural instability and irradiation damage.

After Clementine came the Los Alamos Molten Plutonium Reactor Experiments (LAMPRE I and II), an effort to develop a reactor that used molten plutonium, rather than solid, as its fuel. The idea was this: Clementine's solid fuel rods failed as a result of irradiation damage and crystal lattice instability; molten metal doesn't have a crystal lattice so doesn't accrue irradiation damage; therefore, molten plutonium wouldn't suffer the same effects. Theoretically, a



Crystal structures of the six phases of plutonium. Each phase involves a unique arrangement of atoms into a lattice, imbuing the material with specific properties. The alpha phase (α) forms at room temperature and is dense, hard, and brittle. The delta phase (δ), on the other hand, is soft, ductile and less dense, but only forms around 310ºC. The Plutonium Alloy Survey Program wanted to find an element that when added to pure plutonium, would give it delta-phase properties at alpha-phase temperatures. *CREDIT: David Clark, recreated with permission.*

molten plutonium reactor could run for a very long time. There was a large international effort in the 1960s around this idea, but it eventually stalled due to other material compatibility challenges and operational complexity.

Modern nuclear reactor programs still rely on the foundational data gathered from Clementine and the LAMPRE program. Nuclear reactor research moved away from using pure plutonium as fuel, developing instead, uranium and uranium-plutonium alloys, oxides, nitrides, carbides, or molten salts as safer, longer lasting fuels.

Shock physics and studies of how plutonium behaves under extreme pressure also ramped up steadily over the years. The 1970s and 80s saw innovative advances in measurement science, especially for measuring critical dynamic properties like strength and compressibility. New techniques were developed, like explosives-driven shock experiments and radiography methods that were first developed on plutonium analogs, then later used for plutonium under tight control.

Dynamics

Over the last 35 years or so, focus has been on refining the measurements made during the early years and understanding plutonium aging. Los Alamos continues to lead the way in this innovative science, which is among the most vital activities supporting nuclear deterrence.

Plutonium is still alloyed with gallium to make it workable, and it's important to know how those atoms are arranged and whether, as with Clementine, irradiation damage is building up. In the 1990s and 2000s, accelerated aging methods—like spiking plutonium-239 with a more radioactive plutonium isotope to achieve faster irradiation damage—were developed. Dynamic deformation measurements and subcritical experiments in Nevada were also key in the study of plutonium aging. Enough new data was generated during this time to warrant a massive update to The Plutonium Handbook, the authoritative technical guide to plutonium science, expanding it from its original two volumes in 1967, to seven volumes in 2019.

A boon to plutonium science came in 2012, when researchers at Los Alamos achieved the first successful nuclear magnetic resonance measurements of plutonium-239. Nuclear magnetic resonance detects the specific radiofrequency that atomic nuclei absorb in a strong magnetic field. Observing this signal in plutonium opened the door to powerful atom-scale probes of electronic structure and local atomic disorder—both central to understanding how self-irradiation affects plutonium.

Importantly, Los Alamos played a vital scientific and technical advisory role in 2005, following the 1992 closure of the Rocky Flats Plant, near Denver, where plutonium for weapons had been fabricated since 1952. The plant, which was government owned but privately operated, was closed due to environmental concerns. Los Alamos scientists were able to show that the chemical form of plutonium contaminating the site was not soluble in water, and therefore not migrating into subsurface groundwater; however, it was able to be transported by surface soils through wind and surface water erosion. This meant removing topsoil would be an effective cleanup strategy, which indeed it was. The site is now a wildlife refuge.

With Rocky Flats closed, plutonium manufacturing has now returned to Los Alamos, where it all started. "We need to keep science and engineering and production tightly coupled," says chemist and Lab Fellow Dave Clark, who was on the Rocky Flats clean up advisory team. "When manufacturing is isolated from science, failures happen and scientists get brought back in to diagnose."

Plutonium remains vital to national security and irresistible to science. "Beyond its nuclear utility, the science is fascinating," Clark says. "Plutonium's exotic electronic structure gives rise to highly correlated 5f electron phenomena that drive condensed-matter questions and a lot of theory effort." Put simply, plutonium is still one of the most challenging and scientifically productive elements on the periodic table.

Los Alamos was built around the need to domesticate plutonium. Eight decades later, the metal is still strange, still stubborn—and still at the center of the Lab's mission. ■



Ripples on a surface evoke the wave-like nature of quantum particles.

QUANTUM MATTERS

REBECCA McDONALD

Investigating the fundamental properties of matter could lead to revolutionary materials for the future.

When water gets cold enough, it freezes solid because its atomic motion has nearly stopped. But when it gets hot, the water molecules move quickly, turning it into a gas. Helium, on the other hand, behaves very differently. The most common isotope of helium, He-4, stays a gas at extremely cold temperatures, and doesn't become a liquid until −268.9 °C. Then, at just a few degrees colder, −271.1 °C, it undergoes a phase transition into something completely bizarre: a superfluid. Instead of undergoing random motion, the atoms in superfluid helium start moving together in a coordinated way—a macroscopic quantum state. This state eliminates inner friction, allowing fluid helium to climb out of a glass container or remain motionless within if the container is spun.

The fact that helium is a liquid at such low temperatures makes it not only fascinating to study in its own right, but also useful as a research tool. When liquid helium is used to cool metals and other materials to ultra-low temperatures, the atoms in those materials can also behave strangely: their electrons start to move in coordinated, or correlated, ways, resulting in quantum mechanical phenomena such as superconductivity.

"Cooling materials down to near-absolute zero removes thermal excitations and allows a clearer view of the microscopic properties and the behavior of the electrons," says Filip Ronning, Director of the Los Alamos Institute for Materials Science.

Since the Manhattan Project, scientists at Los Alamos National Laboratory have studied the behavior of materials at cryogenic temperatures, typically below −150 °C. Throughout the

past eight decades, Los Alamos contributed to the development of the field of low-temperature physics and made discoveries about distinct materials. Today, Lab researchers continue to play an important role in the study of quantum effects and in the development of new materials that exhibit those effects, called quantum materials.

"COOLING MATERIALS DOWN TO NEAR-ABSOLUTE ZERO ALLOWS A CLEARER VIEW OF THE MICROSCOPIC PROPERTIES."

Cold, colder, coldest

In the late 19th century, scientists began experimenting with liquefying gases, starting in 1877 when European physicists made a few droplets of liquid oxygen by cooling oxygen gas within a flask under high pressure. Helium, a highly stable and unreactive gas, was the trickiest to liquefy. Helium-4 (He-4), which is naturally abundant in Earth's atmosphere, was first liquefied in 1908 by Dutch physicist Heike Kamerlingh Onnes. Later, Onnes used helium itself as an agent to cool mercury for an experiment in which he discovered the phenomenon of superconductivity. Unlike familiar materials whose structures restrict the flow of electricity and result in energy being lost as heat (e.g., a computer battery gets hot), a superconducting material can carry electricity without any energy loss at all. Onnes won the 1913 Nobel Prize in physics for liquefying helium and discovering superconductivity. Upon further cooling, superfluidity was discovered in He-4 in 1938.

After Onnes's discovery, scientists worldwide began to use helium and other cooled gasses to study materials at low temperatures. In 1945, towards the end of the Manhattan Project, Los Alamos scientists who had cryogenic expertise formed the Metal Physics group to study the unusual physical properties of plutonium at low temperatures. As part of their work on fusion, Lab researchers examined the low-temperature thermodynamic and transport properties of all helium and hydrogen isotopes.

These fusion experiments used the hydrogen isotope tritium, which decays into a rare helium isotope, He-3, giving the team unique access to that far less-abundant isotope. Scientists questioned whether the lighter He-3 isotope, which has one less neutron than He-4, was possible to liquefy. In 1948, Los Alamos's Stephen Sydoriak, Edward Grilly, and Edward Hammel proved He-3 could in fact be liquified below –270 °C, just 3.15 °C above absolute zero.

(In the 1970s, He-3 was also demonstrated to be a quantum superfluid, just like He-4, for which three Americans earned the 1996 Nobel Prize).

The ability to liquify both isotopes of helium was game-changing. In the 1960s, scientists developed a device called a dilution refrigerator that uses a mixture of He-3 and He-4 to produce even colder temperatures, approaching –273.1 °C (0.05 Kelvin)—enabling ultra-low-temperature studies that today allow scientists to thoroughly understand materials from a quantum mechanical perspective.

Electrons are key

In school, students are taught that atoms have a nucleus made of protons and neutrons with electrons orbiting around it. For many of us, that image remains in our minds, but the more deeply people have studied materials, the more they have come to understand the extraordinarily complex and dynamic role electrons play in the properties of matter. Unlike the tidy model, some electrons stay close to their nucleus, some hang out in the outer orbitals and can bond covalently to other atoms to form a molecule, and some are de-localized from any nucleus, enabling the flow of electricity among atoms. The nature of electrons is what makes some materials conductors and others insulators.



Ed Hammel's badge photo from Los Alamos during the Manhattan Project. Hammel was the first group leader of the Metal Physics group and, in 1948, co-discovered that He-3 liquefies at —270 °C.

Cryogenic experiments—using liquid helium as well as liquid nitrogen—helped scientists learn more about unusual phenomena in materials. Ultra-low-temperature studies showed the world that electrons don't always behave as independent particles, and in some materials, their strong interactions with each other lead to strange, correlated behaviors in which the electrons dance in unison like a wave, conducting electricity without any resistance: this is superconductivity.

Building on their early studies of plutonium, Los Alamos scientists used cryogenics to explore questions such as how many plutonium electrons are de-localized and how they are impacted by vibrational excitations. Scientists also began examining all the lanthanides and actinides, the elements most relevant to the materials being used at the Lab.

In the 1970s, Los Alamos scientists applied their expertise in low-temperature physics to the worldwide search for new superconducting materials and to developing superconductivity-based power transmission and energy-storage strategies. Superconductors hold vast potential for a multitude of uses, but known superconductors only did their magic when supercooled with liquid helium, which is hard to come by. If new materials could be found that were superconducting at higher temperatures ("higher" meaning about –196.1 °C, the temperature at which vastly abundant nitrogen liquefies), they could be used for many more applications.

Better yet, the long-sought-after room-temperature superconductor, a holy grail of materials science, would not require cooling at all. For example, normal power lines can lose about 5 percent of electricity during transmission, but superconducting ones could be close to 100 percent efficient. Some superconductors even expel magnetic fields, making them float above strong magnets—which could lead to fast, power-efficient levitating trains.

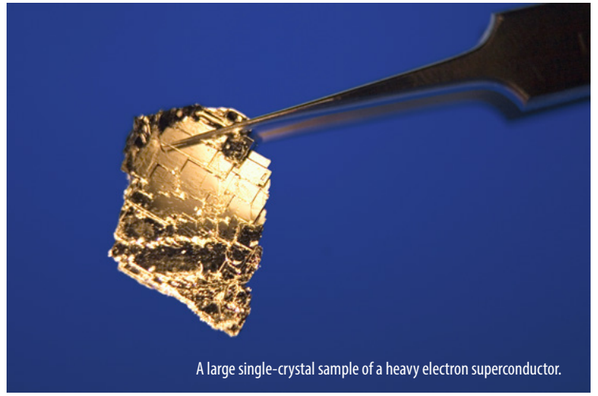
Massive electrons

Although a room-temperature superconductor has not yet been found, hundreds of superconducting materials have been discovered at a range of temperatures, and some are now being used in MRI machines, particle accelerators, and fusion research. Along the way, scientists have thoroughly investigated the atomic characteristics of materials and what happens when they transition from normal metal behavior to strange metal behavior to the emergence of properties like exotic magnetism and superconductivity—leading to fields of study that to this day pose fundamental questions at the forefront of science.

In the mid-1980s, scientists at Los Alamos discovered that superconductivity in certain uranium-based materials was connected to an unusual new phenomenon: electrons that behave as if they have enormous mass. These electrons are not actually heavier than other electrons, but the interactions between them make them appear to have larger mass, because they move about a thousand times slower in certain materials. This characteristic is caused by a nonclassical state of correlation between the electrons called quantum entanglement. This work laid the foundation for a whole new subfield, now called unconventional superconductivity, which studies superconductivity in unexpected materials like copper oxides.

"IT'S RATHER CLEAR THAT QUANTUM MATERIALS WILL PLAY A ROLE IN FUTURE TECHNOLOGIES."

In 1993, Los Alamos added another capability to this field when it became home to the National High Magnetic Field Laboratory's Pulsed Field Facility, which operates high-field electromagnets that are used to study the dynamics of electrons to understand how they move, behave, and interact.



A large single-crystal sample of a heavy electron superconductor.

Making the materials of the future

Today, chemists, materials scientists, and physicists at Los Alamos are using their combined expertise to create new quantum materials and to understand how those materials work at the atomic level. First, the scientists grow novel material crystals by slightly changing the chemistry of a known quantum material. Next, various tests can be done, from studying the sample's thermodynamics to determining its electronic and magnetic properties. Spectroscopic measurements are used to get microscopic information about the material's electronic and magnetic structure under various conditions, and scanning tunneling microscopy or magnetic field measurements can help reveal the behavior of the material's electrons.

With this research, Los Alamos scientists are gaining a comprehensive understanding of which chemistries and structures are associated with a particular material behavior. For instance, in recent years, Lab scientists elucidated that phase transitions in plutonium are driven by strongly correlated electrons, which impact the structural properties of the metal. Ultimately, the knowledge Los Alamos scientists gain will enable the design of materials with specific characteristics to deliver novel functionality.

"It's rather clear that quantum materials will play a role in future technologies, such as quantum computing, neuromorphic computing, or novel detectors of low-energy particles like dark matter and neutrinos," says Ronning.

Just as the silicon transistor revolutionized computing in ways that could not be imagined at the time, quantum materials with new functionalities have the potential to revolutionize computation again. The quantum computers of tomorrow will use these materials to solve problems at a scale, speed, and scope that is currently incomprehensible. ■

SCIENCE OF SIGNATURES:

SEEING THE UNSEEN

Detecting, identifying, and assessing threats begins with recognizing the unique signals they produce—their signatures. Los Alamos studies threat signatures across all domains, whether nuclear, chemical, biological, environmental, or astrophysical.

Indeed, Los Alamos pioneered the science of signatures. From imaging tools developed during the Manhattan Project, like high-speed photography and flash radiography, to more recent inventions like proton radiography and quantum cryptography, Lab scientists and engineers have revolutionized the detection and measurement of a multitude of signatures. Standout areas in which Los Alamos leads are isotope production for medical diagnostics and biomedical research, imaging of extreme processes and novel materials, and quantum sensing to detect otherwise invisible signals.

PROTON POWER FOR PUBLIC HEALTH

ELEANOR HUTTERER



Robotic arms are used to safely handle radioactive medical isotopes contained in a shielded chamber.

How Los Alamos turned nuclear science into a medical marvel.

IN THE 1940S, AS LOS ALAMOS scientists raced to unlock and harness the physics of fission, a parallel scientific revolution was taking shape, one that would take nuclear science from splitting atoms to saving lives: biomedical isotopes.

The science of isotopes was fundamental to the mission at Los Alamos from day one. Some isotopes fission readily, like the uranium used in nuclear reactors (U-235), while others don't, like the uranium found in nature (U-238). The difference boils down to neutrons. Isotopes of a given element have the same number of protons (92 for uranium), but different numbers of neutrons (143 for U-235 and 146 for U-238), meaning they behave the same chemically but differ in mass or radiation emissions.

These differences mean both stable and unstable isotopes can be used as labels. Stable isotope mass measurements can be compared to identify the ratio of particular isotopes that is present. Unstable isotopes emit radiation that can be detected. These characteristics make isotopes powerful, nondisruptive tracers and probes for living systems. As Manhattan Project scientists formed a deep practical understanding of isotope separation, enrichment, and measurement methods, visionary researchers saw vast potential in biomedicine. Through the 1940s and 1950s, Lab scientists turned that understanding from wartime nuclear physics toward broad, exploratory science.

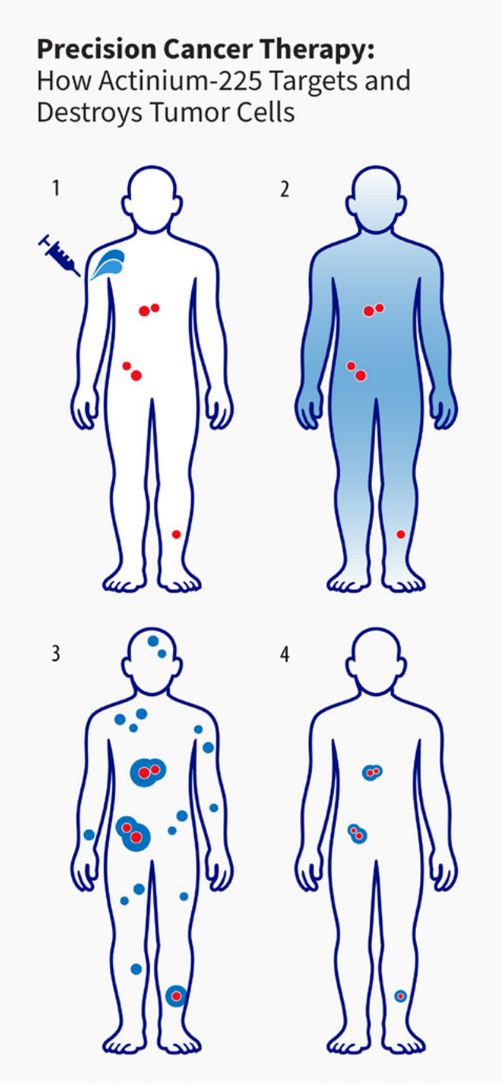
THROUGHOUT THE 1950S, LOS ALAMOS ADVANCED BOTH THE SCIENCE AND THE SUPPLY CHAIN THAT TOOK NMR FROM A PHYSICS CURIOSITY TO A CORNERSTONE TECHNIQUE IN CHEMISTRY, BIOLOGY, AND MEDICINE.

Stable isotopes

Los Alamos was one of the world's first producers of enriched stable isotopes, which are useful as nonradioactive molecular tracers. When measured as ratios of heavy to light, like carbon-13 to carbon-12, stable isotopes can reveal information about metabolic or pathologic processes. They can also be used to selectively strengthen otherwise weak atomic signals, allowing new types of nuclear measurements.

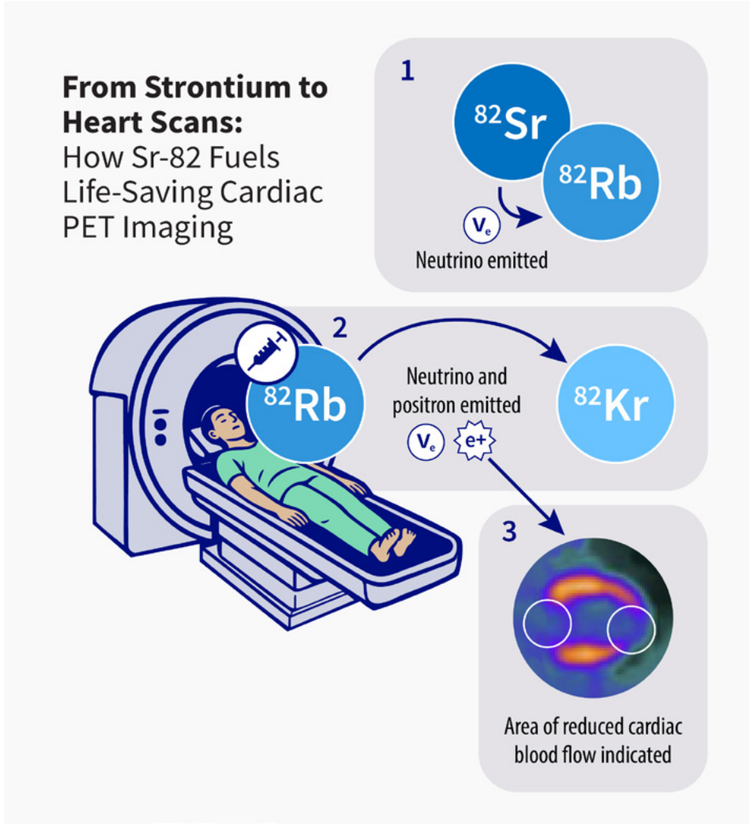
Carbon-13, for example, was essential to the development of nuclear magnetic resonance (NMR) spectroscopy, which enables today's magnetic resonance imaging (MRI) and a slew of other applications in which precise, non-destructive chemical and structural measurement is needed. Carbon-12 is the dominant form of carbon in nature, but because it has no magnetic moment, it's invisible to NMR, which uses magnetic field maneuvers to detect certain nuclei. So, to make biochemicals measurable by NMR, some of their carbon-12 atoms have to be replaced with carbon-13, which has an unpaired nuclear particle, giving its nucleus a magnetic moment and making it visible to NMR. Throughout the 1950s, Los Alamos advanced both the science and the supply chain that took NMR from a physics curiosity to a cornerstone technique in chemistry, biology, and medicine. Other key spectroscopic, or molecular-interaction, techniques developed during this time that relied on Los Alamos–made stable isotopes include Raman spectroscopy, electron spin resonance, and surface plasmon resonance.

During the 1970s and 1980s, Los Alamos pioneered the large-scale isolation of stable isotopes using enormous distillation columns, the largest extending down nearly 700 feet into the ground. The columns were so tall because they used evaporation and condensation to physically separate isotopes by mass, but because the mass difference was so slight—just one neutron—it took many cycles of inching the lighter isotopes toward the top and the heavier isotopes toward the bottom to get adequately pure populations. For more than 20 years, the Lab was home to the National Institutes of Health's Stable Isotope Research Resource, which supported frontier research in basic biology and biomedicine. While production of stable isotopes at Los Alamos has dwindled, having been successfully transitioned to industry, production of unstable isotopes, or radioisotopes, continues in force today



Cancer Therapy. Between 2014 and 2018, Los Alamos joined Oak Ridge and Brookhaven in a tri-lab effort to produce actinium-225 (Ac-225), a rare alpha-emitting isotope capable of destroying tumor cells with pinpoint precision. Here's how that works:

(1) The patient receives an injection of Ac-225 that has been chemically linked to antibodies or molecules that seek out tumor-specific markers.
(2) The Ac-225 circulates through the body and concentrates on tumor cells bearing the right markers.
(3) As the Ac-225 decays inside or near the cancer tissue, its alpha emissions cause lethal damage to cancer cells while sparing most surrounding healthy tissue.
(4) Over time the Ac-225 decays, eliminating the radiation source from the patient's body and leaving tumors significantly smaller in size.



The radioisotope strontium-82 (Sr-82) is an important biomedical isotope because it decays into rubidium-82 (Rb-82), the tracer used in cardiac positron emission tomography (PET). Here's how that works:

(1) A Sr-82 nucleus is proton rich and unstable, so it undergoes a process called electron capture: an inner atomic electron is absorbed, causing a proton to become a neutron, thereby changing the nucleus from Sr-82 (38 protons and 44 neutrons) to Rb-82 (37 protons and 45 neutrons). The process also results in the emission of an electron neutrino.

(2) The Rb-82 is injected into a patient who is inside a PET scanner. Rb-82 is still not stable, so again an electron is absorbed, a proton becomes a neutron, and a neutrino comes out. But this time, a positron is emitted along with the neutrino, and the nucleus, now krypton-82 (Kr-82; 36 protons, 46 neutrons), is finally stable.

(3) Positron emission is the key to cardiac imaging. After injection, Rb-82 is quickly absorbed by the heart muscle in proportion to blood flow. As Rb-82 decays into Kr-82, each emitted positron travels a couple millimeters then annihilates with an electron to generate two gamma photons. These photons are detected by the PET scanner and used to construct high-resolution images showing any areas of reduced blood flow, a sign of coronary artery disease. This β^+ decay process, as it's known, and the short half-life of Rb-82, powers safe, high-speed, high-resolution modern cardiac imaging.

and powers vital medical imaging and treatment on a global scale.

Unstable isotopes

Radioisotopes decay at predictable rates, becoming other isotopes or even other elements, by emitting different types of radiation. It's the radiation that enables medical imaging and therapy. Rubidium-82 (Rb-82), for example, is used in cardiac PET (positron emission tomography) imaging and allows real-time visualization of blood flow and heart function. But Rb-82 is short-lived, lasting just over a minute. So, the trick is to start with strontium-82 (Sr-82), also a radioisotope but one that lasts weeks rather than minutes. The pathway goes like this: unstable Sr-82 converts a proton into a neutron and emits a neutrino, thus becoming Rb-82; Rb-82 is also unstable and converts another proton into a neutron, emits another neutrino and a positron, and stops decaying as a stable isotope of krypton. The emitted positron is what enables medical imaging, but because Rb-82 decays so quickly, it has to be produced onsite from a Sr-82 source as needed for PET imaging. The ability to produce, purify, and distribute large quantities of Sr-82 fundamentally changed how coronary artery disease is diagnosed and managed, and Los Alamos made it happen.

Before the 1970s, the Lab had a cyclotron accelerator to produce protons for physics research. Isotopes were made at the end of the beamline where the protons were dumped afterwords. But in 1972, the substantial radiochemistry capability that had amassed at Los Alamos was formalized into the Medical Radioisotope Program and backed by a proton accelerator within the brand new Los Alamos Meson Physics Facility. Designed to study subatomic particles, the same accelerator could fire high-energy protons into metal targets to force a redistribution of neutrons among atoms and create more isotopes more easily.

Sr-82 was one of the first isotopes the program produced, but making it wasn't the only challenge—equally difficult was extracting it from the cocktail of radioactive fragments that came off the beamline. Lab scientists had to invent new purification chemistry to separate the micrograms of useful Sr-82 from the kilograms of irradiated target material. In the late 1970s, Los Alamos became the first site to routinely produce Sr-82 for medical imaging.

The Medical Radioisotope Program grew through the 1980s, and in 1988 the Department of Energy's Office of Nuclear Energy launched the Isotope Production and Distribution Program (now the DOE Isotope Program) to consolidate isotope production and make it self-supporting through commercial sales. The program grew into a world-class and reliable supplier of both Sr-82 for cardiac imaging and germanium-68 as a calibration standard for PET imaging, as well as a broad suite of more unusual isotopes including copper-67 for cancer treatment.

"THE LAB'S ACCELERATOR-BASED ISOTOPE SUPPLY CHAIN SUPPORTS RESEARCH INSTITUTIONS AND COMMERCIAL PARTNERS ACROSS THE U.S. AND LENDS RESILIENCE AGAINST FOREIGN DEPENDENCE OR GLOBAL SHORTAGES."

By the late 1990s, demand continued to grow and the program needed its own purpose-built proton beam to produce more isotopes more efficiently and at greater purity. So, in 2004, the Lab opened the Isotope Production Facility (IPF), complete with a dedicated proton beam split off from the main accelerator. The IPF was part of a bigger revamp and rebrand of the Los Alamos Meson Physics Facility into today's Los Alamos Neutron Science Center. In 2005, the IPF shipped its first commercial-scale batch of Sr-82 to a major healthcare company, proving that the new facility could not only make the vital isotope, but could deliver it at meaningful scale. Rb-82 PET imaging is more accurate and less invasive than alternative methods of diagnosing coronary artery disease, and it's use continues to rise, with hundreds of thousands of scans done each year in the United States.

"The history of isotope production at Los Alamos is impressive, as is its national and global impact," says Eva Birnbaum, former manager of the Isotope Production and Distribution Program at Los Alamos. "The program also made significant scientific contributions in nuclear data and radiochemical separations related to isotope production. The Isotope Production Facility itself is a flagship facility for proton-based isotope production."

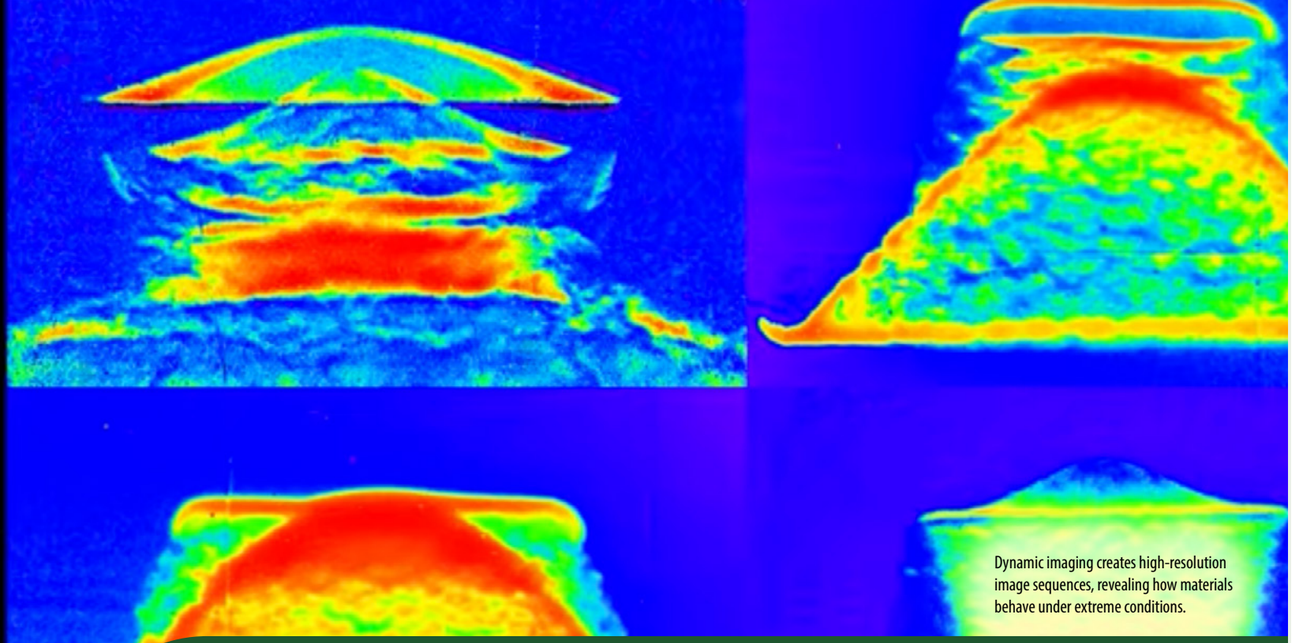
The IPF's scope has expanded to include other isotopes for diagnostic imaging as well as isotopes to actually treat disease, like actinium-225 (Ac-225). Ac-225 is an alpha-emitter that can be targeted, via antibody or molecular tag, at tumor cells, concentrating in and destroying them with pinpoint precision. One atom of Ac-225 emits four separate alpha particles as it decays into stable bismuth-209. The alpha particles' high energy is destructive to living cells, but their slow speed limits their range to nearby tumor cells while sparing surrounding healthy tissue. Between 2014 and 2018, Los Alamos joined Oak Ridge and Brookhaven national laboratories in a tri-lab initiative to produce Ac-225. The collaboration demonstrated the ability to close a critical supply gap that had previously left the U.S. dependent on foreign or legacy stockpiles.

Secure supply chain

"The Lab's accelerator-based isotope supply chain supports research institutions and commercial partners across the U.S. and lends resilience against foreign dependence or global shortages," says Kevin John, Office of Science Program Director and also a former manager of the Isotope Production and Distribution Program at Los Alamos.

Indeed, production of Sr-82 and other isotopes has now successfully been transferred to industry, and commercial Ac-225 production is being scaled up. This transfer of established technologies to the commercial sector allows innovators at the Lab to shift focus to new isotopes for fresh applications.

Beyond isotope production, Los Alamos drives discovery in radiochemical separation, target design, and accelerator operation, while also training the next generation of scientists in nuclear chemistry and health physics. These capabilities underwrite U.S. leadership in both isotope science and biomedical technology and ensure a domestic supply of the isotopes that are essential to public health and national security. ■



Dynamic imaging creates high-resolution image sequences, revealing how materials behave under extreme conditions.

FLASH PHOTOGRAPHY

REBECCA McDONALD

Los Alamos scientists pioneered techniques to photograph extremely fast phenomena such as implosions.

During the Manhattan Project, Los Alamos scientists needed a diagnostic tool. Like an x-ray confirming a broken leg bone, the researchers wanted to be able to see into the smoke cloud of detonation products. They needed to verify that the implosion remained symmetric to ensure an efficient detonation. Although it was a time when scientific breakthroughs came quickly, this challenge stumped them, and their initial efforts to use x-rays to visualize the event were limited. According to Manhattan Project historian David Hawkins, "These objectives were pursued relentlessly, but because of the great technical difficulties involved, with little real success. The program was dropped in March 1945."

"I find this quote very interesting because it shows just how difficult it is to create these dynamic images," says Scott Watson, Laboratory Fellow, who has, over his 38-year career, taken hundreds of images of explosions. Despite the setback in 1945, Los Alamos scientists went on to pioneer several capabilities to visualize and evaluate dynamic events, leading to key elements of today's national security mission.

Can you see it?

Scientists during the Manhattan Project designed the first atomic device as a sphere of high explosives with a metal core. When the high explosives were detonated, they would implode and compress the metal core symmetrically from all around.

"They wanted to be able to create a uniform implosion," says Watson. To tackle this challenge, the team used surrogate metals to model the assembly and timing of the compression process. Flash radiography was then used to image the implosion, allowing scientists to verify whether the design performed as predicted.

"PHERMEX WAS THE WORLD'S FIRST PURPOSE-BUILT FLASH RADIOGRAPHIC FACILITY."

Flash radiography directs high-energy particles, such as electrons, to collide with a target, making x-rays that penetrate the metal core (like the way that x-rays pass through a broken bone). Unfortunately, radiographs in 1944 were primitive; the energy of x-ray sources wasn't high enough to fully penetrate the core, and the researchers were left with images of its contour instead. To address this, the scientists also tried using higher-energy x-rays produced by a type of accelerator called a betatron. The resulting images were helpful enough to get to the finish line of the Manhattan Project but not ideal, with a spatial resolution of only a centimeter. After the war, scientists were able to more thoroughly dive into the challenge of dynamic imaging and by the 1960s had begun to make real progress.

PHERMEX the pioneer

In 1961, Los Alamos scientists succeeded in generating enough high-energy photons to create flash x-ray images of explosive devices, and in 1963, the Lab opened a facility called PHERMEX: the Pulsed High-Energy Radiographic Machine Emitting X-rays. PHERMEX was the world's first purpose-built flash radiographic facility and included many unique technological advances along with the world's largest radio-frequency cavities. It was the first of a new generation of machines able to deliver enough energy to penetrate the metal core to create dynamic images with resolution approaching a millimeter.

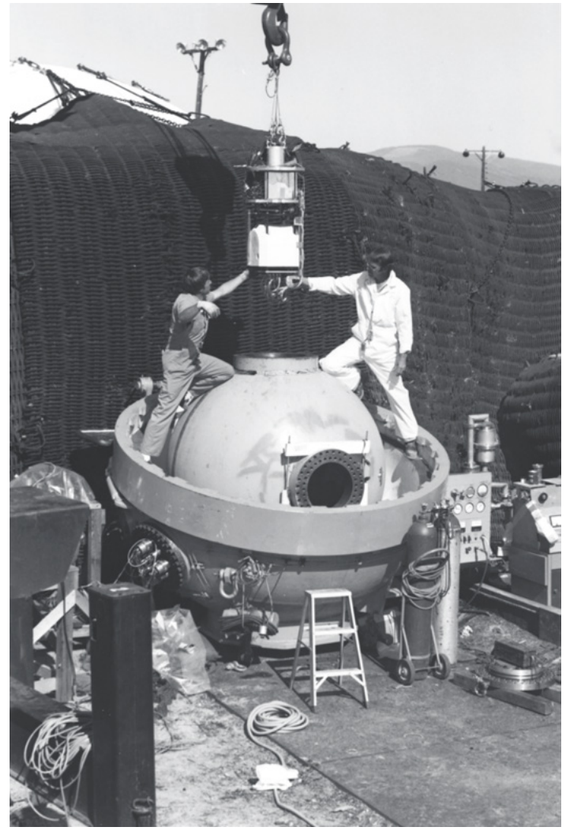
PHERMEX enabled thorough analysis of surrogate materials used to replace the fissile components in a nuclear weapon by using three large 50-megahertz radio-frequency resonators, which provided the electron beam with the energy needed for thousands of explosive experiments. Scientists used PHERMEX to confirm their design using the surrogate materials, enabling iterative tweaks. In addition, PHERMEX was used to study the fundamentals of how various materials respond in the extreme environment of a nuclear weapon—such as how they compress or expand with changes to volume, temperature, or pressure. These so-called equation-of-state data were collected for hundreds of materials, leading to an invaluable data catalog and benefitting a multitude of physics research endeavors.

PHERMEX provided vital images to the scientific community and underwent several upgrades, which increased the strength of its particle beams and changed the types of detectors to enable the highest-resolution images possible. In the 1990s, radiography became even more important for national security. For example, data on materials and implosions could be used to verify how aging weapons were expected to perform. After more than 40 years of service, PHERMEX was eventually retired, but new generations of dynamic imaging machines were developed to carry its mission forward.

A suite of capabilities

Scientists strived over the years to improve dynamic imaging tools to collect more radiographic images with improved resolution. The forces experienced in an implosion far exceed the materials' strength and, therefore, the materials flow like liquids—prompting the experiments to be called "hydrotests." As a result, a single, static picture often fails to capture the evolution of the implosion process.

Los Alamos scientists envisioned a new approach that would use two perpendicular beams of electrons to produce x-rays, enabling multiple pictures to be taken from two angles of an implosion inside a containment vessel. To realize this vision, the Lab built the Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility, which



Historical photo of confinement vessel at the Lab's PHERMEX (Pulsed High-Energy Radiographic Machine Emitting X-rays). PHERMEX was used for 40 years to visualize explosions using flash radiography.



Lowering an experiment into the containment vessel at the pRAD facility at the Los Alamos Neutron Science Center (LANSCE). Los Alamos scientists invented proton radiography to take advantage of the unique properties of high-energy protons to capture multiple images of a detonation.

began operation in the early 2000s and has completed over 100 hydrotests as a key part of the US dynamic imaging capability. In addition to having higher-current electron beams than PHERMEX and a smaller x-ray source spot size, DARHT incorporates a unique array of thin tubes in the image collection system, called a Bucky grid, to collimate the x-rays, improving contrast by rejecting scattered x-rays. High-speed, high-sensitivity cameras capture the unique, rapidly evolving aspects of the implosion. Images from two angles provide three-dimensional details, which cannot be identified in a single radiograph, at a higher resolution.

In addition to the DARHT facility, Los Alamos maintains an open-air firing capability called the Area 1 Firing Sites. The Firing Sites use multiple x-ray sources and detectors arranged at several angles and without the constraints found at DARHT. Scientists use this arrangement to image metal cases and their dynamic response when driven by high-explosive detonations, a technique called case radiography.

A third capability at Los Alamos uses protons instead of x-rays to create dynamic images of implosions and explosions. Taking advantage of the existing 800-million-electronvolt proton beam at the Los Alamos Neutron Science Center, Los Alamos scientists invented a new technique called proton radiography, or pRad, in 1995. The pRad facility uses the unique properties of high-energy protons to capture multiple images of a detonation. pRad employs seven solid-state, high-speed cameras that capture 21 images in a few microseconds. The result is a stop-motion radiographic movie of the explosion, giving a unique set of data for researchers not available by other methods.

“USING DARHT, THE AREA I FIRING SITES, AND PRAD, LOS ALAMOS SCIENTISTS GENERATE IMAGES AND DATA THAT ARE CRITICAL TO THE LABORATORY’S MISSION.”

Beyond the mesa

Using DARHT, the Area 1 Firing Sites, and pRad, Los Alamos scientists generate images and data that are critical to the Laboratory’s mission. Scientists at these facilities also work together with the larger dynamic imaging effort across the National Nuclear Security Administration complex, including Cygnus and the Flash X-Ray Facility.

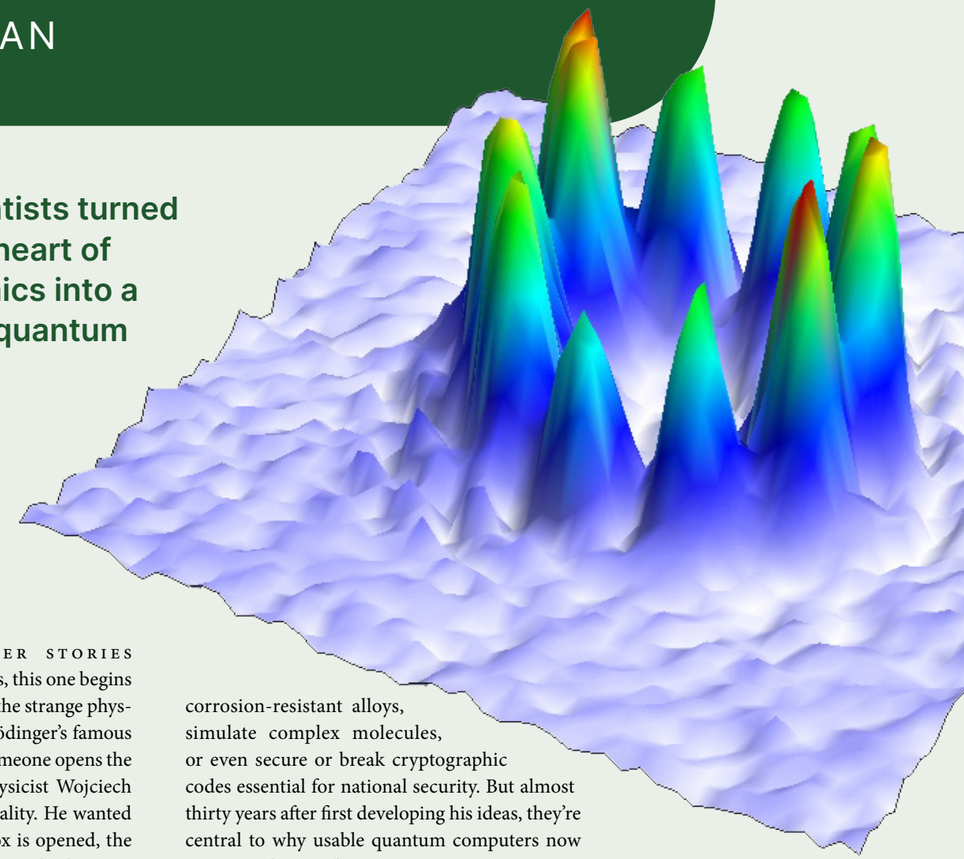
Another capability, Scorpius, is a new accelerator project under construction at the Nevada National Security Sites. Scorpius will use an electron beam that can be broken into customized pulses to deliver x-rays and capture multiple images many microseconds apart.

Stemming from the earliest Manhattan Project–era attempts at visualizing implosions, Los Alamos has pioneered high-speed photography and radiography techniques that are now essential to national security. Today’s coupled capabilities ensure that our nation’s scientists have the tools they need to understand the nature of weapon components and how to safely assess the national stockpile. ■

THE RACE TO BUILD A QUANTUM COMPUTER

KYLE DICKMAN

Los Alamos scientists turned a paradox at the heart of quantum mechanics into a pathway toward quantum computing.

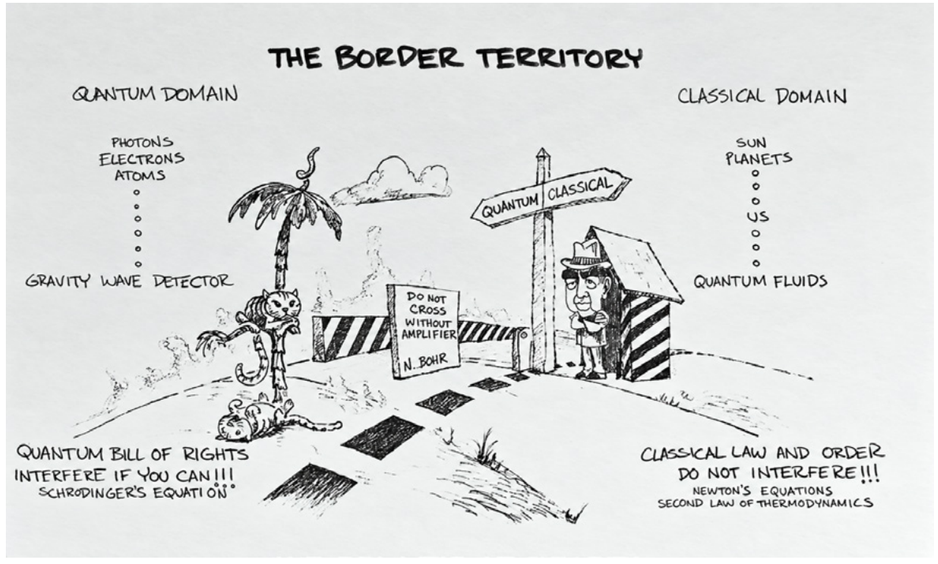


The building blocks of tomorrow: an ultra-cold structure helping scientists study the physics needed for quantum computers.

LIKE TOO MANY OTHER STORIES ABOUT quantum mechanics, this one begins with a cat in a box. According to the strange physics of the subatomic world, Schrödinger’s famous cat is both alive and dead until someone opens the box. Los Alamos theoretical physicist Wojciech Zurek accepted that oddity as reality. He wanted to understand why, when the box is opened, the cat is always dead or alive—but never both.

More precisely, Zurek sought to explain how the fuzzy, probabilistic rules governing atoms give way to the definite, stable reality we experience through a process called decoherence, in which interactions between quantum systems and their environment produce classical behavior. Zurek’s decades at Los Alamos were largely theoretical—whiteboards, quiet hours, long conversations about even longer equations. He didn’t set out to build a quantum computer that could help design corrosion-resistant alloys, simulate complex molecules, or even secure or break cryptographic codes essential for national security. But almost thirty years after first developing his ideas, they’re central to why usable quantum computers now appear within reach.

By the early 1980s, the classical computing revolution was well underway. Personal computers were entering homes and offices, while supercomputers at national laboratories were pushing the limits of numerical simulation. Moore’s Law promised ever more powerful machines. Yet even as classical processors grew faster, they remained bound by the same binary logic: bits encode information as zeros and ones, and every calculation is executed through long sequences of binary steps.



A cartoon illustrating Wojciech Zurek's "border territory" between the quantum and classical worlds, where decoherence governs the transition from superpositions to everyday reality. These ideas have become central to efforts to build scalable quantum computers.
CREDIT: Wojciech Zurek

Richard Feynman, the Nobel Prize–winning physicist who had worked at Los Alamos during the Manhattan Project, recognized that because of this, classical machines would always struggle to simulate the quantum world. "Nature isn't classical, dammit," he told an audience in a 1981 lecture. "And if you want to make a simulation of nature, you'd better make it quantum mechanical."

At its most fundamental level, matter obeys the rules of quantum mechanics, in which physical systems, like Schrödinger's cat, can exist in combinations of multiple states at once. In the early 1980s, Feynman and British physicist David Deutsch, often called the father of quantum computing, recognized that this strange reality could form the basis of a new kind of machine. Quantum computers would encode information in quantum bits, or qubits, which can exist in combinations of zero and one—a state known as a superposition.

"NATURE ISN'T CLASSICAL, DAMMIT. AND IF YOU WANT TO MAKE A SIMULATION OF NATURE, YOU'D BETTER MAKE IT QUANTUM MECHANICAL."

When multiple qubits are linked through a phenomenon called entanglement, they become a single, unified quantum state in which each qubit's behavior depends on the behavior of the others. A quantum algorithm can then evolve that unified state, using interference to amplify certain outcomes, so that when the qubits are measured, the resulting pattern reveals the solution. Long before anyone could point to a specific application, Feynman and Deutsch understood that entangled qubits hinted at unusual computational power. As more qubits become entangled, the size of that joint state doubles with each added qubit, so that representing it on a classical computer would require resources beyond what even the most powerful supercomputers are capable of.

But there was a catch. The same delicate quantum behavior that made such machines intriguing also made them fragile. Heat, stray electromagnetic fields, and interactions with the surrounding environment can disrupt the delicate relationships that allow superposition and entanglement to persist. This disruption is known as decoherence. For a quantum computation to succeed, coherence must survive long enough for the calculation to finish. Without a way to manage decoherence, the idea of a scalable quantum computer remained largely theoretical.

Even if decoherence could be solved, the real problem was that no one knew why it was worth solving. As the American theoretical physicist John Archibald Wheeler put it, "To encounter the quantum is to feel like an explorer from a faraway land who has come for the first time upon an automobile. It is obviously meant for use, and important use, but what use?"

That answer began to emerge in 1994, when mathematician Peter Shor of AT&T's Bell Laboratories showed that a sufficiently powerful quantum computer could efficiently factor large numbers, the mathematical foundation of modern cryptography. In a single paper, quantum computing shifted from thought experiment to strategic priority. If such machines could be built, they would be able to break or fortify many of the encryption systems that secure global finance, communications, and national defense.

Building one, however, required confronting decoherence, the same phenomenon Zurek had been studying for decades. Soon after Shor's discovery, Zurek and his Los Alamos colleagues Emanuel Knill and Raymond Laflamme asked a practical question: if decoherence inevitably introduces errors into a quantum computation, could those errors be corrected before they accumulate and derail it? The problem was paradoxical. Errors must be detected to be corrected. But detecting them seemed to require measuring a qubit—and measurement collapses the very state the computation depends on.

HOW DO THE FUZZY, PROBABILISTIC RULES GOVERNING ATOMS GIVE WAY TO THE DEFINITE, STABLE REALITY WE EXPERIENCE?

The answer lay in changing what was being measured. In the mid-1990s, Zurek, Laflamme, Knill and their colleagues showed that the quantum information representing a computation could be encoded across multiple entangled qubits rather than stored in a single one. That redundancy allowed errors affecting individual qubits to be detected indirectly—without measuring and collapsing the fragile computational state itself. Their work did not build a quantum computer. But it demonstrated that scalable quantum computation was not forbidden by the laws of physics.

Over the next two decades, researchers advanced along that path. By the mid-2010s, a series of technical breakthroughs ushered in what Malcolm Boshier, a physicist at Los Alamos, calls the second wave of quantum computing. If the first wave proved quantum computing was not forbidden by physics, the second asks whether it can scale. Los Alamos now plays a central role in answering that question.

After decades studying decoherence, error correction, and quantum computing algorithms, the Lab plays a major role in the Quantum Benchmarking Initiative (QBI), a Department of Defense and Defense Advanced Research Projects Agency-supported effort to rigorously evaluate competing quantum-computing designs. Rather than build machines, QBI evaluates proposed architectures through technical scrutiny, asking a practical question: Can the quantum architecture scale to deliver performance that justifies their cost?

Today, quantum processors have grown from a handful of qubits to hundreds—and in some cases, thousands. They remain noisy and error-prone. But the conversation has shifted. The question is no longer whether they are possible, but what will it take to make them useful.

Alongside this evaluative role, the Lab continues to advance quantum science—developing precision sensors and refining the algorithms and error-correction methods that underpin computation. Yet the broader question remains open. Quantum computers are clearly powerful tools, but exactly how they will reshape science, industry, and national security is still being mapped.

This past year, Los Alamos researchers identified another problem for which quantum computers could hold a decisive advantage: the efficient simulation of large optical circuits—networks of beam splitters and phase shifters acting on vast numbers of light modes. Such circuits underpin emerging photonic technologies used in secure communications, precision sensing, and next-generation quantum computing architectures. As these systems scale, predicting their behavior becomes exponentially difficult for classical machines, which must track a myriad of possible interference patterns. A quantum computer, governed by the same physical laws as the light moving through those circuits, can in principle simulate them far more naturally—and far more efficiently.

In a sense, the problem fulfills Richard Feynman's original challenge. If nature is not classical, he argued, then our simulations should not be either. Identifying domains where quantum systems can efficiently model other quantum systems marks one of the first clearly defined arenas in which that vision could translate into practical advantage. "At the moment, you can count such problems on two hands," says Marco Cerezo, who led the work. "That's the Holy Grail of quantum computing."

For Boshier, the story of quantum follows a familiar pattern at Los Alamos. Ideas that once seemed purely theoretical matured quietly, sometimes for decades, before revealing their practical force. "Twenty years after Zurek, Laflamme, and Knill's key ideas were first developed, they're only now starting to look like they can deliver a tangible product," he says. "That's the nature of exploratory science." ■

COMPLEX NATURAL
AND ENGINEERED SYSTEMS:

FROM PROTEINS TO PLANETS

Complex systems—whether natural or artificial—rarely behave as expected. Los Alamos scientists and engineers study how systems' components interact, adapt, and evolve to produce emergent behavior.

Los Alamos has transformed the study of complex natural systems, like forest fires and permafrost, as well as complex engineered systems, like energy grids and nuclear weapons. The invention of the flow cytometer revolutionized biology by enabling detailed single-cell analysis, and combined with early genomic research at the Lab, helped lay the groundwork for the Human Genome Project. Los Alamos–made sensors travel aboard satellites and spacecraft, mapping lunar hydrogen, studying the surface of Mars, and exploring the edges of our solar system. The whole is often greater than the sum of its parts and the Lab therefore takes an integrative and comprehensive approach to addressing the nation's most complex scientific challenges.



A hydrogen fuel cell golf cart made at Los Alamos Scientific Laboratory in the 1970s.

FIFTY YEARS OF FUEL CELL INNOVATION

REBECCA McDONALD

The Los Alamos fuel cell program has contributed to advancing the industry since the 1970s.

HYDROGEN FUEL CELLS ARE NOT NEW. IF YOU remember watching the movie Apollo 13, you might recall that when an oxygen tank ruptured, it imperiled the fuel cells that gave the astronauts electricity and drinking water. Although the earliest attempts at fuel cells were made in the 1800s, space program scientists in the 1950s, along with General Motors employees, developed electrochemical fuel cells to convert hydrogen and oxygen into electrical power and water for spacecraft. These fuel cells were critical power sources on the Gemini and Apollo missions; they weighed less than batteries and could last longer. Fuel cells were key to manned missions and remained invaluable components in space travel for decades.

And then, during the energy crisis of the 1970s, scientists began to wonder if hydrogen fuel cells could be used for vehicles here on Earth. The spacecraft fuel cells were far too expensive to consider and did not have the durability needed for cars, but perhaps science could help. In 1977, a group of researchers at Los Alamos Scientific Laboratory (now Los Alamos National Laboratory) got a twenty-five-thousand-dollar-Laboratory Directed Research and Development grant to develop fuel cells for ground transportation. This investment launched the Lab's fuel cell program, which proceeded to make seminal innovations that underlie all of today's transportation fuel cells and more.

THE LOS ALAMOS FUEL CELL PROGRAM MADE SEMINAL INNOVATIONS THAT UNDERLIE ALL OF TODAY'S TRANSPORTATION FUEL CELLS.

Pull out the platinum

In the beginning of the Los Alamos fuel cell program, scientists made demonstration vehicles to show off their ideas. First, they modified a passenger car and a pickup truck to use hydrogen for fuel. Then, they developed a golf cart that drove using a hydrogen-oxygen phosphoric acid fuel cell instead of a battery—it was efficient and gave off only water vapor as emissions, what could be better?

Hydrogen fuel cells are similar to batteries: they have two electrodes (anode and cathode) and use the energy from chemical bonds to drive electrons through an external circuit. Key to the technology is a polymer electrolyte membrane, which separates the electrodes and contains a catalyst to facilitate the reaction—as such, the resulting product is often referred to as a polymer electrolyte fuel cell (PEFC). (Another common term, PEMFC, refers to the polymer electrolyte membrane fuel cell or proton exchange membrane fuel cell). One of the challenges that faced Lab scientists was that the best catalyst was also the most expensive: pure platinum metal. The researchers set out to find a way to reduce the amount of platinum needed (or find an alternative catalyst), increase efficiency, and ensure the durability of the fuel cells.

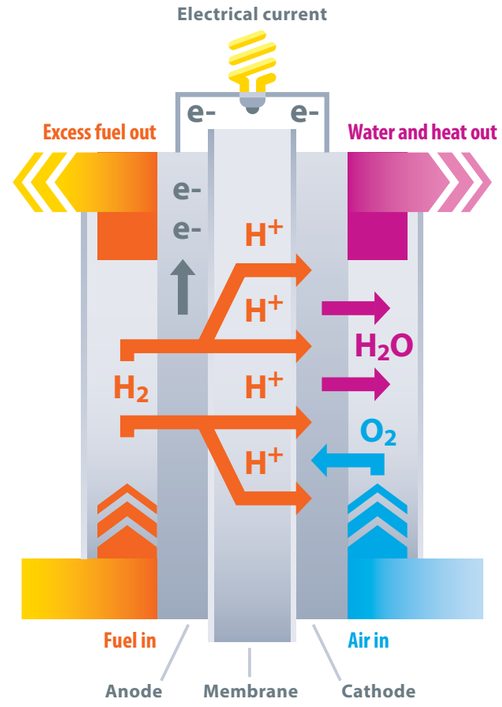
In the 1980s, the Los Alamos fuel cell program grew significantly and began to make pivotal advances. One of the most important breakthroughs was the development of a thin-film, low-platinum electrode.

"This innovation dramatically lowered the required amount of platinum by a factor of more than 20, while simultaneously improving performance," says Rod Borup, recently retired Los Alamos fuel cell scientist and Laboratory Fellow. The 1980s team also improved the structure and composition of the thin-films to ensure their durability without loss of performance. Fuel cell manufacturers worldwide currently use this low-platinum approach.

Hope for hydrogen

In 1991, Los Alamos established the General Motors Joint Development Center. This collaboration was an effort funded by General Motors and the Department of Energy (DOE) to facilitate the development of an electrochemical engine—a PEFC system fueled by hydrogen-rich gas produced on demand from a methanol precursor. This approach stood to mitigate the challenge of hydrogen availability, as the country lacked infrastructure to provide on-demand purified hydrogen.

However, the process of converting methanol to hydrogen-rich gas sometimes left carbon monoxide in the mix. This impurity in the hydrogen negatively impacted fuel cell performance. Los Alamos scientists mitigated this challenge by developing PEFCs that could operate using impure hydrogen fuel. The scientists figured out that by bleeding low levels of air into the fuel feed



Schematic of a hydrogen polymer electrolyte fuel cell (PEFC). The fuel cell has two sides, each with an electrode (anode and cathode), separated by a polymer electrolyte membrane that keeps the chemistry on the two sides from mixing. The fuel (hydrogen gas) is channeled into the anode side and air (containing oxygen) is channeled into the cathode side.



A Los Alamos–made material for the membrane of a hydrogen fuel cell that is optimized for larger vehicles.

stream, they could remove the carbon monoxide catalytically. This development paved the way to more widespread use of PEFCs.

Over the decades, the Los Alamos fuel cell team continued to collaborate with industry partners to further improve fuel cells, looking to develop new platinum-free cathode catalysts, to improve fuel cell lifetime and durability, and also to innovate around new sources of hydrogen. In 2016, Los Alamos partnered with Argonne National Laboratory to form the ElectroCat Consortium dedicated to investigating non-platinum-group metal catalysts.

"Even with our thin-film electrode approach, the platinum needed still accounts for about 40 percent of the cost of the fuel cell," says Los Alamos electrochemist and Lab Fellow Piotr Zelenay, who continues to lead the Consortium. "Replacing it with a platinum-group-metal-free catalyst would give the ultimate savings."

FUEL CELLS ARE INHERENTLY SCALABLE AND COULD BE ADAPTED TO ANYTHING FROM PORTABLE ELECTRONICS TO HOMES.

Beyond cars

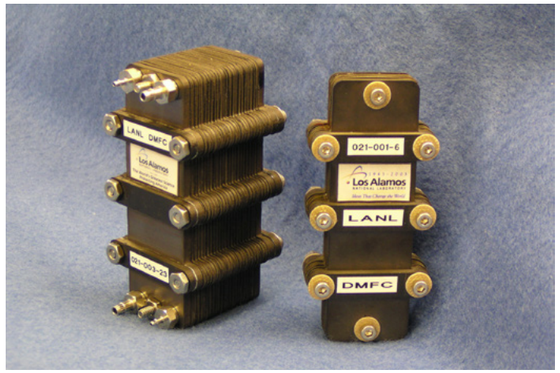
Around 2014, some scientists began to shift focus to the nearly four million diesel semitrucks driving back and forth across America.

"The DOE fuel cell program switched to heavy duty vehicles and trucks," says Zelenay. "For trucks, batteries are not practical due to their prohibitive size and weight, but hydrogen fuel cells showed potential as an alternative solution." In 2020, the DOE launched a consortium, co-led by Los Alamos and Lawrence Berkeley national laboratories, to advance new types of fuel cells.

Scientists faced new challenges to adapt hydrogen fuel cells for heavy-duty vehicles. The fuel cells used in passenger cars operate at a specific temperature, but the amount of power needed to drive a semitruck would produce excess heat and render the fuel cell inoperable. Developing high-temperature hydrogen fuel cells would require implementing new types of materials, which they did.

Among the growing list of achievements, one group of Los Alamos researchers produced and patented a completely new type of membrane and electrode combination called "protonated PWN70," which stands to accelerate the use of fuel cells for heavy-duty vehicles. The new materials are not only efficient at the right temperatures but also durable. Today, the consortium, which is called Multi Modal Fuel Cell Technologies (M2FCT), continues to focus on future energy needs. Although it is no longer prioritizing trucks, the scientists are looking broadly at energy needs and even stationary applications.

"Fuel cells are inherently scalable," says Borup. "Through our decades of experience working on polymer electrolyte fuel cells, we can adapt these technologies to anything from portable electronics to homes." In fact, they've already demonstrated it. In the early 2000s, Los Alamos fuel cell scientists worked with a few industry partners to improve performance and miniaturize direct methanol fuel cells (DMFCs), which rely on high-density liquid methanol and don't require conversion to hydrogen. Small, portable DMFCs are attractive as lightweight alternatives to batteries for laptop computers and other small electronics.



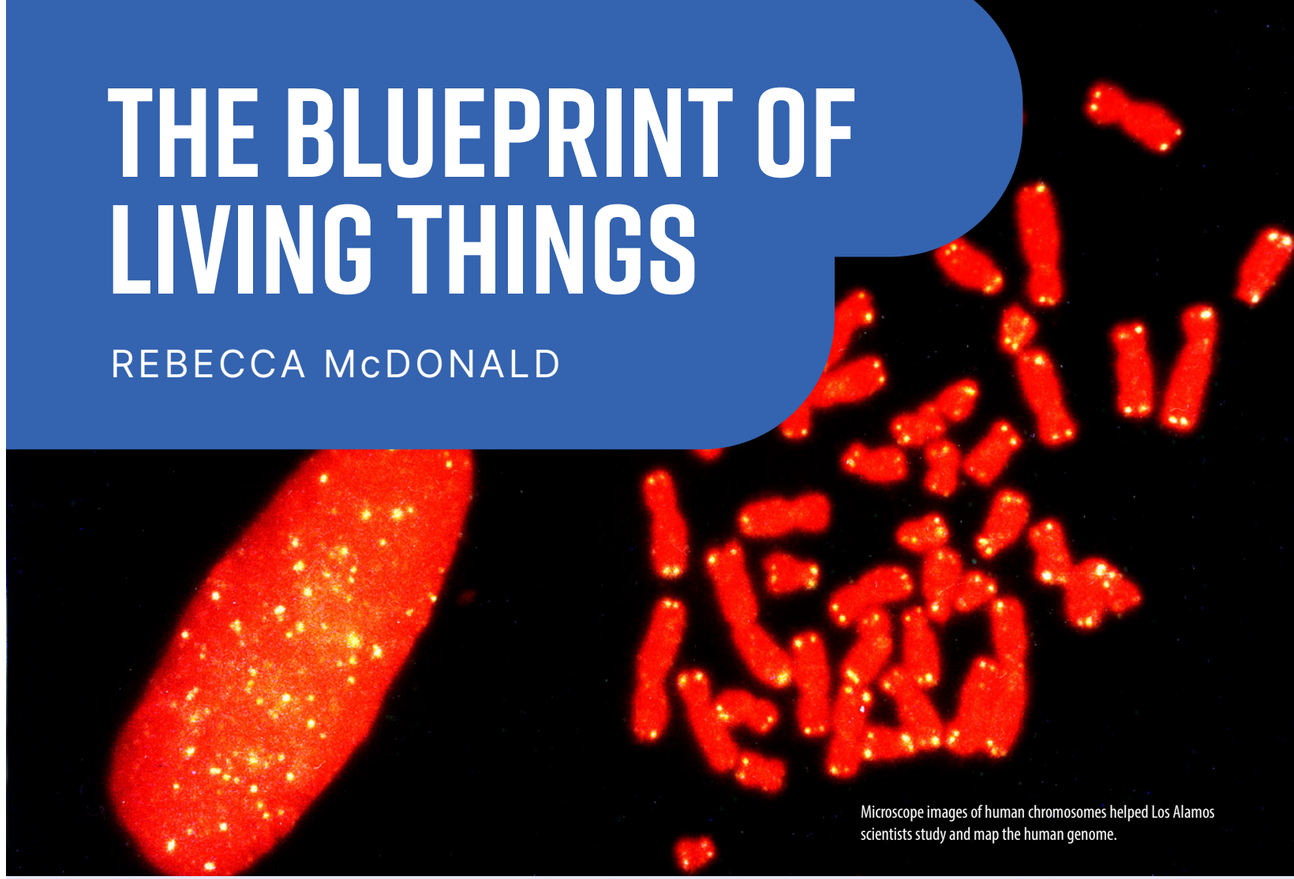
Stacks of 6- and 25-cell DMFCs using 19.6 cm2 cells. The larger stack can generate up to approximately 80 W of power, while only weighing about 250 g.

The fuel cell story is far from complete. In 2014, Toyota began to market its hydrogen fuel cell car, the Mirai ("future" in Japanese), in Japan and California. Today, thousands of fuel cell–powered cars are being used in the U.S., and a handful of car manufacturers have fuel cell vehicles for sale in various markets around the world.

For nearly five decades, Los Alamos scientists have demonstrated success in developing hydrogen fuel cells for any need, and in the decades to come, one can only imagine the innovative ways that fuel cells will be a part of our lives. ■

THE BLUEPRINT OF LIVING THINGS

REBECCA McDONALD



Microscope images of human chromosomes helped Los Alamos scientists study and map the human genome.

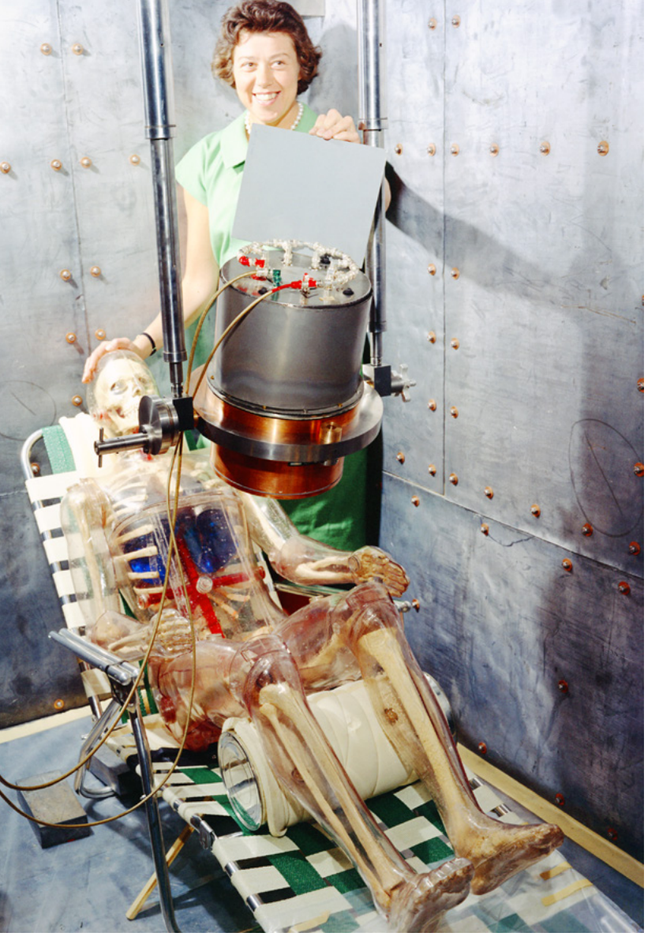
How innovation at Los Alamos helped launch the Human Genome Project and the genomics revolution.

In March 1986, a group of scientists (including several from Los Alamos) gathered in Santa Fe, New Mexico, to discuss the possibility of sequencing the entire human genome. Until then, while exciting and potentially valuable, the endeavor had not been considered feasible. Unraveling the blueprint of human beings could improve understanding of genetic disease and cancer, leading to advances in health care and prevention. People worried, however, that sequencing the genome would cost too much, that the technology was not readily available, and that it would require a level of international collaboration beyond anything scientists had done before.

The Santa Fe meeting was pivotal. It generated exciting ideas and momentum about how to address the technology challenges, and the scientists—including Los Alamos's Scott Cram, Larry Deaven, and Robert Moyzis, who were awarded the Los Alamos Medal in 2017 for this work—helped the program leaders develop a plan forward. In 1987, the Department of Energy (DOE) began moving forward with a pilot Human Genome Initiative. Not everyone in the scientific community was excited, in fact, dozens wrote letters in opposition citing concerns about the "big science" nature of the project and the fact that a large percentage of the genome was likely "junk DNA." Despite opposition within the National Institutes of Health (NIH), in 1988, the agency partnered with the DOE in the congressionally funded official Human Genome Project (HGP)—which today is regarded as one of the greatest achievements in science. The HGP has led to innumerable advances for human health and for understanding our relationship with the living world.

Why DOE?

Although it seemed unusual to many that the DOE was taking the lead to sequence the human genome, Los Alamos scientists didn't think it was unusual at all: they had been laying the groundwork for decades.



A woman prepares for a test with Plastic Man, a life-sized dummy made to hold real bone and tissue samples for whole-body radiation studies.

Beginning with the Manhattan Project, the DOE's predecessor, the Atomic Energy Commission, was charged with conducting research on the health effects of radiation. By then, radiation had been linked to cancer, but scientists did not understand the underlying mechanisms or if these cancers would be heritable to the next generation. The Commission wanted to understand how radiation could impact its employees, the military, and anyone or anything exposed to it.

During the 1940s and 1950s, scientists at Los Alamos investigated this idea of "health physics." In one project, to explore the effects of whole-body radiation exposure, Los Alamos chemist Wright Langham built "Plastic Man," a life-sized dummy made to hold real bone and tissue samples. As biology advanced and scientists learned more about the molecular make-up of organisms (such as the 1953 discovery of DNA's structure), it became logical to change focus from animal tissues to the cells and molecules within them. Perhaps understanding DNA could elucidate how it might be impacted by radiation.

Over the next few decades, several distinct projects happening in parallel at Los Alamos helped lay the foundation for the technologies used in the HGP for sequencing and analysis. In the 1960s, scientists figured out how to read DNA by deciphering its sequences. By the 1970s, sequencing was becoming widespread in the scientific community and a handful of Los Alamos physicists—who had turned their attention to biology and computation—realized that the accumulating sequence data would need a repository. Physicist Walter Goad and his team established the Los Alamos Sequence Database in 1979, populating it with published sequences and developing the computational framework to efficiently share this collection with the greater scientific community for comparative analysis. In 1982, the database was renamed GenBank, and it was housed at Los Alamos until 1992 when it was moved to the NIH. GenBank now holds more than 4.7 billion sequences for more than half a million species.

In another Los Alamos group, in the 1960s, scientist Mack Fulwyler made a device to count, sort, and identify individual cells. This device led to the development of modern-day flow cytometers and cell sorters, which are now ubiquitous throughout medical and research laboratories worldwide. In 1982, Los Alamos began the NIH-funded National Flow Cytometry and Sorting Research Resource through which scientists developed new types of flow cytometers and research techniques. In addition, Los Alamos joined with Lawrence Livermore National Laboratory for the DOE National Laboratory Gene Library Project, in which they used flow cytometry to create copies of human chromosomes for distribution to researchers. This capability was critical in the early days of the HGP because it ensured that enough copies of a specific chromosome's DNA would be available for sequencing. During the HGP, Los Alamos played a key role in providing chromosome-specific DNA libraries to partner institutions, while focusing in-house efforts on the sequencing of chromosome 16 and parts of chromosome 5 (each participating institution was assigned different chromosomes).

Beyond its role in the HGP, Los Alamos was a founding partner in the DOE's Joint Genome Institute (JGI) in 1997, and Lab scientists continued to hone sequencing protocols, curate databases, and develop the new field of bioinformatics to computationally turn the increasing amount of data into actionable information.

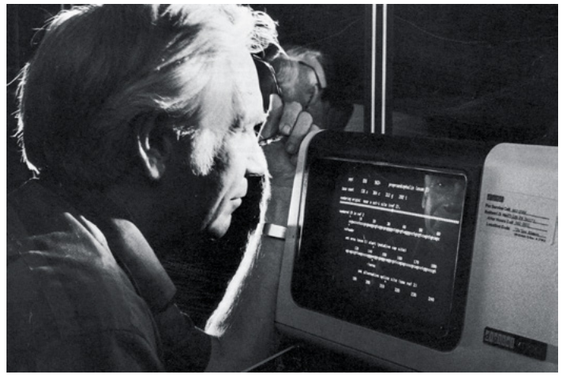
Next generation genomics

When the HGP officially launched, DNA sequencing was a tedious, labor-intensive process that cost a dollar or more per base pair, putting the price tag of the entire project to over three billion dollars.

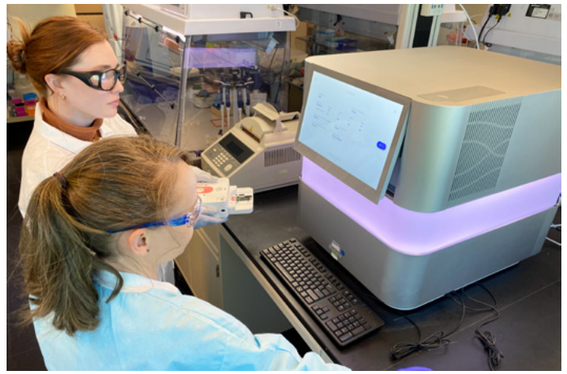
"We started the HGP without knowing what the technology would be like when we finished it," says biologist and Laboratory Fellow Babetta Marrone. "We needed the project to revolutionize the tech."

A technology revolution is precisely what happened. The HGP was expected to take 15 years, but after several twists and a lot of drama, the genome was delivered two years early, in 2003, along with a disruptive new technique called shotgun sequencing that transformed the future of genome science completely. Every year that followed saw advances in sequencing machines and techniques, making it easier and exponentially less expensive to sequence genomes. Today, the cost per base pair is approximately one tenth of a cent.

Throughout this revolution, Los Alamos scientists, the JGI, and several other institutions began applying the new sequencing methods and technologies to a variety of microorganisms and animals to more thoroughly investigate their evolutionary relationships, how they function, and how they interact. In addition, building on the idea of GenBank, Lab computational biologists compiled species-specific databases, the first one being a Human Immunodeficiency Virus (HIV) database created in 1986 by Lab scientist Gerald Myers in response to the AIDS pandemic. Recognizing HIV's extraordinarily rapid rate of evolution, the data helped researchers track the virus's evolution and diversity. Myers's database enabled the comparative analysis of pathogen genomes, leading to strategies for vaccine and therapeutics development, and informed epidemiological tracking of viruses through populations.



Walter Goad, founder of GenBank, looking at sequence data in 1984.



Scientists setting up sequencing run on an Illumina sequencing machine. Los Alamos scientists use several types of next-generation sequencers for today's research projects.

WE STARTED THE HUMAN GENOME PROJECT WITHOUT KNOWING WHAT THE TECHNOLOGY WOULD BE LIKE WHEN WE FINISHED IT.

In its earliest days, the HIV database was provided to researchers annually as a hardcopy book. Computational biologist and Lab Fellow Bette Korber, who led the HIV database for 25 years after Myers retired, remembers visiting labs where the book was actually chained to people's desks to keep others from walking off with it. Today, the HIV database is available online with close to a million HIV sequences, and the Lab hosts additional databases for Human Papilloma Virus, influenza, Hepatitis C, ebolavirus, and even SARS-CoV-2, the virus that causes COVID-19.

Omniscient 'omics

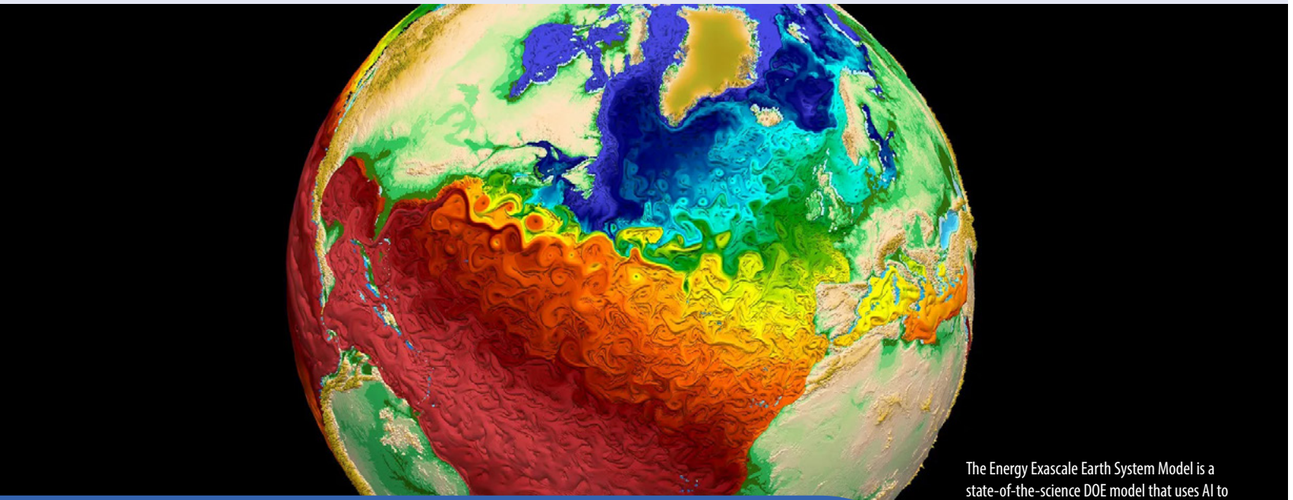
Because of the technological advances spurred by the HGP, scientists can now routinely evaluate new genomes (genomics), RNA and gene regulation (transcriptomics), chemical modifications to genes that can influence their regulation (epigenomics), and identify encoded proteins (proteomics) and chemical signals (metabolomics). These technologies, used independently, or together (called multi-omics), allow Los Alamos scientists to explore human disease and normal function, host-pathogen interactions within an organism, and the spread of pathogens through humans and animal populations.

"As SARS-CoV-2 was just beginning its global expansion, we rapidly adapted computational tools we had first developed to study HIV sequence evolution, and this enabled us to discover, in 2020, that SARS-CoV-2 was evolving to be more infectious," says Korber. Throughout the COVID-19 pandemic, Los Alamos scientists helped track variants, supporting discoveries in near-real-time regarding how specific mutations impacted vaccine efficacy, transmission, and drug and antibody resistance.

Los Alamos scientists have also helped pioneer the new field of microbiome science, which is the study of the assemblage of microbes that live within an environment such as a human gut or skin, an algae pond, or a corn field. The ability to elucidate threats in these types of complex environments profoundly enhances the nation's security through understanding the conditions and organisms that promote healthy plants and animals compared to those that cause disease.

"We are employing traditional bioinformatics and new tools driven by AI, to analyze in real time, large volumes of sequencing data," explains computational biologist and Lab Fellow Patrick Chain. "For instance, using data from an environment like wastewater we can try to anticipate novel and emerging pathogens, predict their potential for spread, their evolution, and what diagnostics and countermeasures can be deployed to mitigate their impact."

It is unlikely that the scientists irradiating Plastic Man in the 1950s anticipated that their work would begin a trajectory towards tracking biothreats through global populations and their sewers, but it is an undeniable example of how basic scientific research feeds an unlimited future of discovery. ■



The Energy Exascale Earth System Model is a state-of-the-science DOE model that uses AI to make global and regional predictions.

THE PLANET INSIDE A COMPUTER

KYLE DICKMAN

How Los Alamos scientists turned Cold War supercomputers into engines of planetary insight.

In the fall of 1983, a thin plume of simulated smoke appeared inside a Los Alamos supercomputer. The smoke—nothing more than computer code on a cathode-ray display—wafted across continents, dimming them in gray. The image was digital and silent, but to the physicists watching, it felt apocalyptic. That was the point.

Earlier that year, astronomer and science communicator Carl Sagan had warned that a global nuclear war could ignite cities and forests, lofting soot high into the atmosphere, blocking sunlight, and triggering what he called a "nuclear winter." Agriculture would collapse; entire ecosystems could fail. The idea triggered well-justified alarm. But was it true? At the Lab, physicist Bob Malone, hired years before to build an Earth system modeling program, was tasked with testing the theory.

Malone began building one of the first three-dimensional atmospheric models ever used for Earth systems research—a vast numerical experiment that simulated how smoke, heat, and radiation would circulate around the planet. "It was completely unprecedented," says Elizabeth Hunke, an applied mathematician and Lab Fellow who later worked with Malone's team. It was also prescient.

The sky would darken, yes—but according to the model, the world would not freeze. Having answered the question, Malone came to understand that the same methods used to model nuclear smoke could also model Earth's climate, not just the planet's destruction. By the time Malone's group finished its simulations in 1985, a new computing revolution was underway with Los Alamos at its center. The Department of Energy (DOE) had launched the CHAMMP program, Computer Hardware, Advanced Mathematics, and Model Physics, to bring Earth systems modeling into the age of massively parallel supercomputers. What began as an exercise in national security evolved into one of the world's most sophisticated efforts to understand the climate as a coupled, dynamic system. That understanding would help answer essential national security questions.

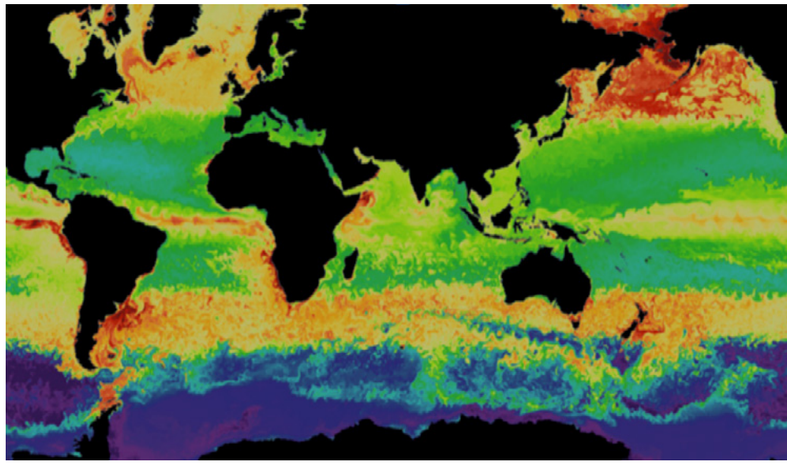
"WHAT BEGAN AS AN EXERCISE IN NATIONAL SECURITY EVOLVED INTO ONE OF THE WORLD'S MOST SOPHISTICATED EFFORTS TO UNDERSTAND THE CLIMATE AS A COUPLED, DYNAMIC SYSTEM."

Earth system modeling is necessarily a distributed field. Modeling Earth's web of interconnected systems requires scientific expertise as diverse as the systems themselves. A single global model depends on hundreds of different scientists and software engineers, often located at institutions around the world. But it also requires computers powerful enough to weave the myriad systems together into one model. Los Alamos, one of the world's high performance computing centers, offered exactly this advantage. "The Lab's access to high performance computing accelerated the entire field of Earth system science," Hunke says.

With the nuclear-winter question largely settled, Malone and his team turned Los Alamos's computing power to one of Earth system science's biggest unknowns—the ocean. In the 1990s, atmospheric modeling was already dominated by experts at the National Center for Atmospheric Research and the Geophysical Fluid Dynamics Laboratory, but few teams were focused on the role the oceans play in dictating climate.

"Fluid dynamics was our language," Malone says years later. The same physics describing the turbulence created by explosions could be used to describe ocean currents and eddies. Malone's small team soon developed the Parallel Ocean Program, or POP—the first ocean model designed for distributed-memory computers. Its innovations—local boundary conditions, a realistic moving sea surface, and a new surface-pressure formulation—made it both faster and more accurate than anything before it.

As the world's Earth system modelers dug deeper into the field, they found more questions than answers. Individual models that represented single systems—the ocean, the atmosphere, ice sheets, land, forests, rivers—improved when they worked together. "Earth behaves as a complex adaptive system. Understanding how individual components are coupled together is key to predictions of the system as a whole," says Andrew Roberts, a Los Alamos–modeler who works on today's Energy Exascale Earth System Model, a state-of-the-science DOE model that uses AI to make fast and accurate global and regional predictions. But back when Earth system models were in the earliest stages of development, one glaring omission was sea ice.



An early version of the Parallel Ocean Program models how the oceans circulate.

"You can't accurately simulate the Earth system, let alone the oceans, without it," says Hunke. Sea ice does more than freeze, melt, and drift around the poles. It caps the polar oceans, reflecting sunlight and regulating the planet's temperature gradient, which drives near- and

long-term weather patterns across the globe. But modeling the physics of sea ice was so complex and computationally expensive that the era's best models represented it like molasses—slow, stiff, viscous, and prone to crashing computers because the calculations needed to represent it were so demanding.

Hunke arrived at Los Alamos in 1994 as a postdoc and teamed up with mathematician John Dukowicz with the goal of making an accurate sea-ice model that could run within a full Earth system simulation—without crashing it. "What we did at Los Alamos," Hunke says, "was figure out how to make a physics-based model of sea ice efficient enough that it could run on supercomputers of the day."

She and Dukowicz's new code captured the physics of how real ice freezes, melts, fractures, jams, and drifts and is so accurate that thirty years later, the model is still used to forecast the state of our polar oceans by countries around the world—from the U.S. to Norway, Australia, and South Korea.



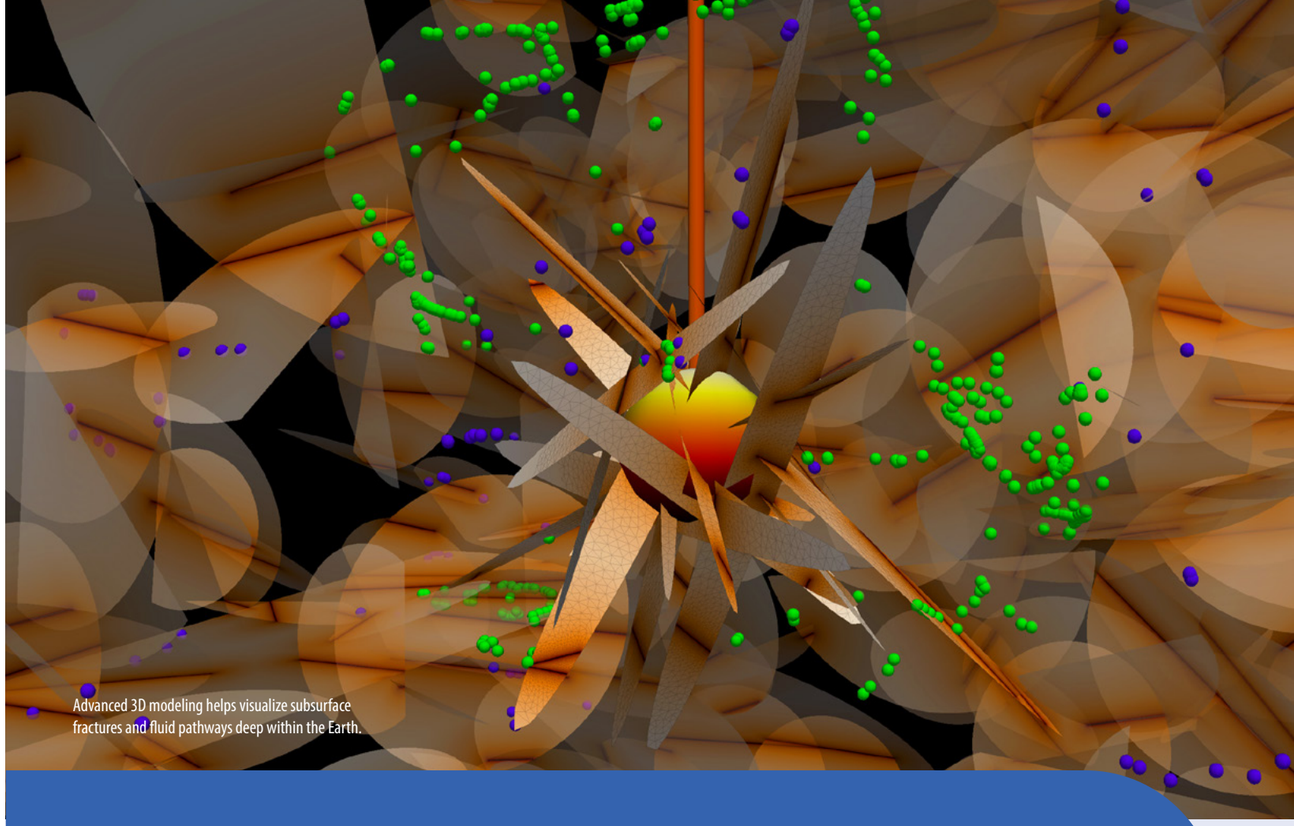
Los Alamos scientist Elizabeth Hunke holds an ice core during a research trip to Utqiaġvik, Alaska.

"YOU GET MUCH MORE OF THE EARTH SYSTEM WHEN YOU HAVE ALL THE COMPONENTS TALKING TO EACH OTHER, THROUGH FEEDBACKS."

In the decades that followed, Los Alamos widened its reach. The Lab built the first physics-based wildfire model and extended its ice simulations to the Greenland and Antarctic ice sheets. "Those are critical components for understanding national security questions," says Matt Hoffman, who leads a project to refine how Earth system models represent the Antarctic.

To gather the data that feeds these models, scientists took to the field. They measured aerosols and trace gases, tracked drought-killed forests, and folded those data back into models to improve global and regional predictions. By the 2010s, the Lab's focus had stretched from Arctic tundra to tropical forests, from power grids to methane leaks. "Now we're adding full biogeochemistry to our models—everything from aerosols and atmospheric chemistry to plankton and algae," says Elizabeth Hunke.

Today, each new model generation gets closer to both Earth's mirror and crystal ball, reflecting how the planet works and hinting at what it might yet become. "But there is still so much more to do to get there," says Roberts. ■



Advanced 3D modeling helps visualize subsurface fractures and fluid pathways deep within the Earth.

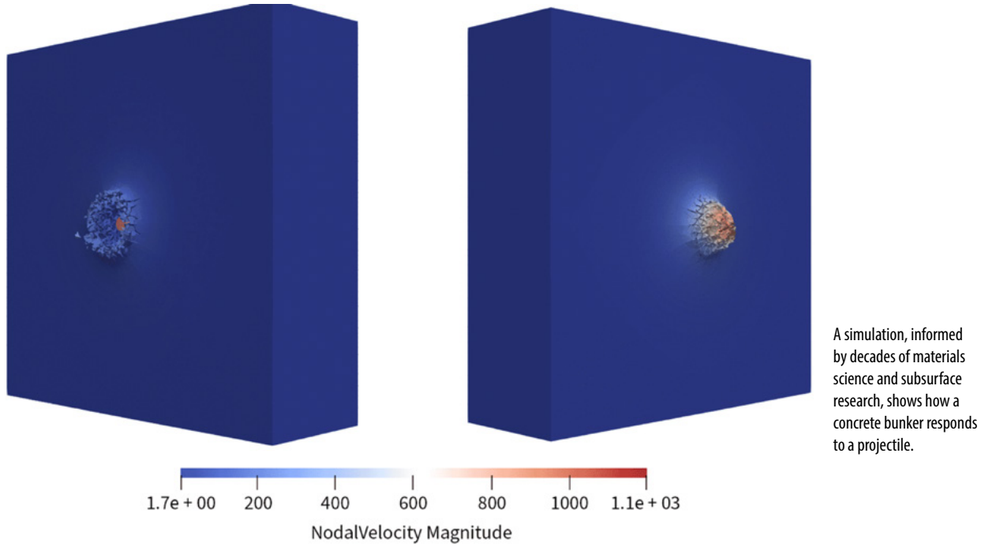
THE TRANSPARENT EARTH

KYLE DICKMAN

Los Alamos is turning its deep expertise in Earth's subsurface—and new advances in AI—into a clearer picture of the planet beneath our feet.

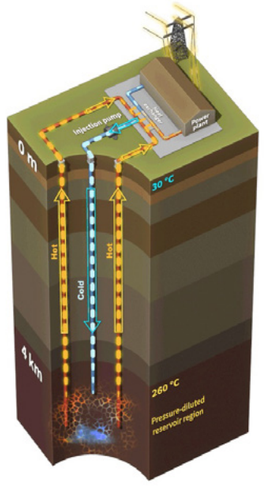
IN THE FALL OF 2025, A PRESENTATION WAS GIVEN TO THE U.S. Secretary of Energy and a handful of defense officials on some of Los Alamos National Laboratory's latest computing research. One slide showed a model of a projectile striking a block of material and cracks spiderwebbing out from the impact. "Bunker busting," says Hari Viswanathan, a geologist at Los Alamos whose work was being presented. "Our goal was to predict how materials fracture before they fail."

The work looked and sounded like weapons science. It was. Yet the models that guided the design of bunker-busting projectiles were born out of decades of Lab research into the Earth's subsurface.



A simulation, informed by decades of materials science and subsurface research, shows how a concrete bunker responds to a projectile.

By the 1970s, a pair of global oil shortages drove Los Alamos scientists to begin looking for energy alternatives in the subsurface. For one source, they turned to the hot rock beneath the 11,000-foot volcanic peaks of the nearby Jemez Mountains. At a site called Fenton Hill, they drilled two wells—each nearly three miles deep—into granite and rhyolite heated by ancient volcanic activity to about 250–300 °C. Cold water was pumped into one, where it cracked the rock and formed a network of tiny fractures. From the second well, steam billowed to the surface, spinning a turbine.



At the Fenton Hill geothermal test site near Los Alamos, scientists drilled two wells nearly three miles deep into hot, dry rock. Cold water pumped into one well fractured the rock, creating a network of cracks that circulated heat. The resulting steam rose through a second well to drive a turbine and generate electricity—demonstrating that geothermal reservoirs could be engineered where none naturally exist.

At the time, it was known that geothermal electricity generation was feasible. But the Lab scientists, led by the geologist Donald W. Brown, showed at Fenton Hill that hot, dry rock could be artificially fractured and that by circulating water through that cracked rock, it was possible to create geothermal reservoirs where none existed before. That work paved the way for ongoing Department of Energy projects like the Frontier Observatory for Research in Geothermal Energy in Milford, Utah, where the agency hopes to show that geothermal power is both commercially scalable and viable at many sites in the continental United States.

Whether the goal is to contain an explosion, store waste, or harvest heat, success depends on understanding the physics of how rock breaks—or doesn't—and moves. "All subsurface models, no matter what question they're helping answer, require the same physics," Viswanathan says. From the 1980s into the 2020s, that knowledge of fluid flow, fracture mechanics, and the ability to predict what could not be seen fed the Lab's growth into new programs: nuclear-waste disposal, earthquake prediction, carbon sequestration, or hydraulic fracturing. Yet our understanding of the subsurface remains incomplete.

"YOU DON'T GET TO DIRECTLY IMAGE THE SUBSURFACE. THE BEST YOU CAN DO IS USE GEOPHYSICAL DATA TO GET AN INKLING OF WHAT'S GOING ON."

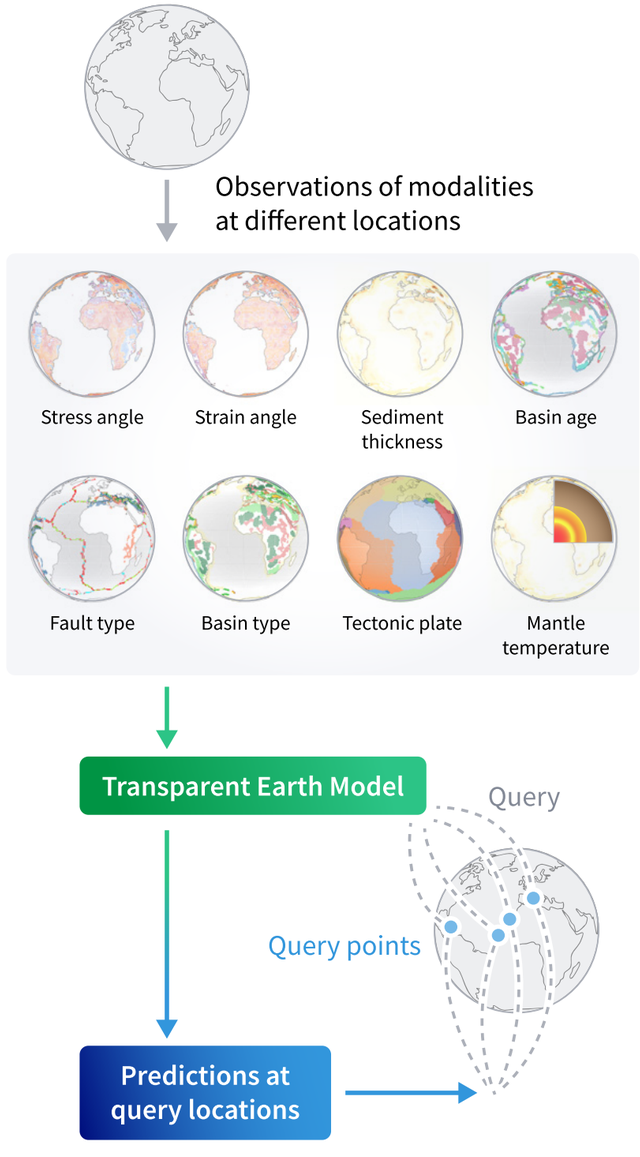
"You don't get to directly image the subsurface," Viswanathan says. "The best you can do is use geophysical data to get an inkling of what's going on." To decode those faint signals, Los Alamos spent decades refining its instruments. Laboratory researchers developed and refined acoustic probes that detect rock strain and used x-ray and neutron experiments at the Los Alamos Neutron Science Center (LANSCE) to watch fractures form under pressure. Insights from those experiments fed high-performance simulations that reproduce the physics of the shallow Earth. Now, the Lab is turning to artificial intelligence (AI) to unite it all.

"THE PHYSICS NEVER CHANGE. THE QUESTIONS DO. THE APPLICATIONS SHIFT WITH THE MOMENT, BUT THE SCIENCE IS ALWAYS ROOTED IN THE SAME FUNDAMENTALS."

Viswanathan compares the way that AI processes diverse information sources to the way that senses emerge and are refined in nature. "It's like a dog's nose," he says. "Each of the many receptors in it isn't extraordinary, but together, they make sense of a world we can't see." That pattern-recognition ability is being put to use in a project led by geoscientist Dan O'Malley that is called Transparent Earth. Building on seven decades of the Lab's subsurface research, the project promises to enable the discovery of new energy sources and deposits of critical minerals, and it could even support global nuclear nonproliferation. The idea is to teach AI to visualize the underground environment by feeding it essentially every available measurement of the subsurface—seismic tremors, magnetic maps, satellite images, drill-core chemistry, even text from decades of field reports by the U.S. Geological Survey. The model learns by combining imperfect signals into a clear picture.

Transparent Earth visualizes those inputs. It fuses the signals into probabilistic maps that predict what lies beneath: where fractures might open during fracking or geothermal exploration, where heat might flow, where critical minerals might hide, and the subsurface temperature in different areas of the continental United States. In the past, those clues would have remained buried in separate datasets.

Viswanathan and O'Malley hope that, with the help of AI, they can fuse decades of scientific data and Lab expertise into a digital twin of the planet's crust—a physics-informed, AI-powered model of the Earth's hidden systems. "The physics never change," says Viswanathan. "The questions do. The applications shift with the moment, but the science is always rooted in the same fundamentals." ■



The Transparent Earth model integrates diverse geophysical data—such as stress and strain angles, sediment thickness, fault type, and mantle temperature—to predict subsurface conditions anywhere on the planet. By combining decades of measurements and simulations, the model uses AI to infer what lies underground in regions where direct observations don't exist—information that could help locate energy reserves, critical minerals, or even drinking water.

THE PLANETS

KYLE DICKMAN



Self-portrait of NASA's Mars rover, Curiosity.

How Los Alamos revealed water—and the promise of life—across the solar system.

In a home office overlooking a well-watered garden in Los Alamos, planetary scientist Nina Lanza watches the surface of the moon ripple across her monitor. Neutron data glow in bands of blue and red. It's a map that shows hydrogen signals puddled on the floor of the moon's permanently shadowed craters—evidence of water in a place that not so long ago was thought impossibly parched. "The moon is going to be a major player in national security," says Lanza. "We need to know what's there."

For Lanza and her colleagues, the search for water on other worlds is more than an academic question. It's the end of a scientific thread that stretches from Cold War origins to the Artemis III mission that in the coming years aims to land astronauts on the moon's southern polar region.

Los Alamos National Laboratory's journey into space began in the 1950s when scientists turned their nuclear expertise skyward with Project Rover, an audacious attempt to use a nuclear reactor as a rocket engine. The project, a collaboration with the Atomic Energy Commission, demonstrated that fission could propel spacecraft, but it also cemented the Lab's reputation for building machines that thrive in extreme environments. A few years later, as the Cold War intensified, Los Alamos engineers pivoted their space research away from propulsion to detection. One primary tool for detecting nuclear detonations was the radiation-sensor equipped Vela satellites. Launched in 1963, these Los Alamos–built instruments watched from orbit for the telltale flash of an atomic blast.

When nuclear weapons detonate, they release an unmistakable flood of neutrons. To detect that signal, Los Alamos scientists equipped the Vela satellites with instruments tuned to the energy and flux of neutrons. Those sensors ended up revealing something beyond their mission: a steady background of neutrons—a signal scientists later understood to be produced when cosmic rays strike matter throughout space, including the surfaces of airless worlds.

In the 1990s, Los Alamos physicist Bill Feldman realized that this phenomenon could reveal water in space. While many elements can slow neutrons, hydrogen does it most efficiently. Its nucleus is nearly the same mass as a neutron, allowing the two to trade energy on impact. That distinctive interaction makes hydrogen stand out in neutron data. On airless bodies like the moon, where hydrogen is almost always bound to oxygen, detecting it becomes a reliable proxy for water. "So if you see hydrogen, it's stuck to oxygen," says Lanza. "That's a pretty good sign you're looking at water."

In 1998, the National Aeronautics and Space Administration (NASA) launched the Lunar Prospector mission to map the moon's composition and its magnetic and gravitational fields. Onboard, at Feldman's bidding, was a Los Alamos–built neutron spectrometer. Within months of reaching lunar orbit, Feldman's instrument had detected elevated hydrogen levels at both lunar poles—a clear indication that the moon's permanently shadowed craters harbored water ice.

Three years later, Mars Odyssey carried an updated version of the instrument to the Red Planet, where it found vast stores of hydrogen in the top meter of soil. The discovery sent a shockwave through planetary science. "Bill built the field," says Lanza. "He changed how we view every rocky planet."

These findings also laid the foundation for Los Alamos's ongoing planetary science work. By the time Lanza joined the team in 2006, Los Alamos was trying to put instruments on planets—not just around them. She joined the ChemCam team and helped put the first laser spectrometer ever sent to another world onto NASA's Curiosity rover. Mounted on the rover's mast, ChemCam fired thousands of laser shots at Martian rocks, vaporizing pinhead-sized patches and reading the spectrum of light from the resulting plasma. "The laser's first shot on Mars showed hydration in the dust," Lanza says. "It confirmed what we'd been seeing from orbit." Water is on Mars.

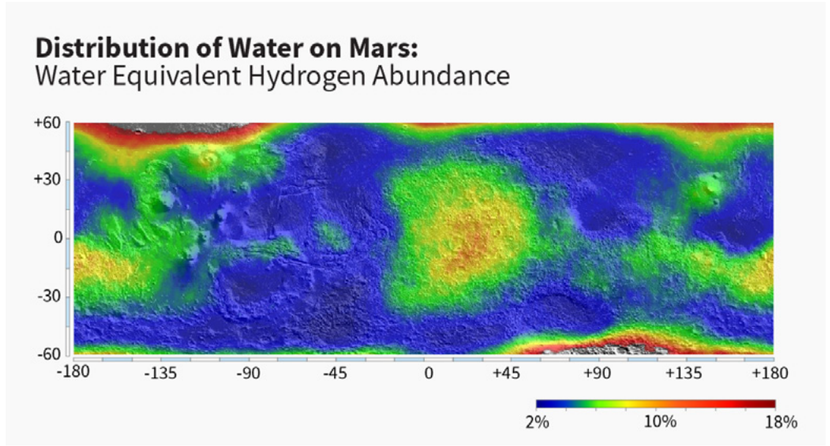
ChemCam's successor, SuperCam, now rides aboard NASA's Perseverance rover, where it adds color imaging, Raman and infrared spectroscopy for identifying minerals and organic compounds, and even a microphone. The instrument captured the first sounds ever recorded on another planet—the crackle of its laser impacts and the whistle of the Martian wind. SuperCam's data have already confirmed manganese oxides in Martian rocks, evidence that ancient Mars once had abundant water and perhaps even oxygen.

With work on Mars ongoing, the Lab's and country's scientific focus has turned closer to home: back to the moon. Potentially rich in critical minerals, home to radio-quiet zones prized for astronomy, and a possible outpost for missions to Mars, the moon has also become a new frontier of geopolitics. "It's the highest possible ground we have and valuable to everybody because of it," Lanza says. "Los Alamos has new scientific questions to answer there."

One possible source of inquiry seems absurdly mundane: the moon's dust. But on its low-gravity surface, the angular, abrasive dust can behave like an accidental weapon. Particles kicked up by a lander's thrusters can travel kilometers at hundreds of meters per second, scouring any equipment it touches. "We're thinking about questions that go beyond science," Lanza says, referring to the accelerating international push to develop infrastructure on the moon. "If China builds something on the moon and we land nearby, what happens to the dust our landers kick up? These are national-security questions now."

Even as exploration grows more complex, the Lab's purpose has remained remarkably constant: to reveal what we can't see, to measure what we can't touch. "Human curiosity leads to discovery," Lanza says. "If you let scientists pull on the threads they're most interested in, they find things you didn't even know existed. That curiosity and careful investigation can change science, technology, and exploration in ways nobody ever imagined." Those changes often benefit national security. ■

"HUMAN CURIOSITY LEADS TO DISCOVERY. IF YOU LET SCIENTISTS PULL ON THE THREADS THEY'RE MOST INTERESTED IN, THEY FIND THINGS YOU DIDN'T EVEN KNOW EXISTED."



This map shows near-surface hydrogen on Mars and was derived from neutron spectroscopy data collected by the Los Alamos–built neutron spectrometer aboard NASA's Mars Odyssey spacecraft. Regions in blue indicate low hydrogen abundance, while warmer colors mark hydrogen-rich areas—evidence of water ice buried just beneath the Martian surface, especially near the poles.



The aurora borealis paints the night sky in vibrant shades of purple and green.

SPACE SCIENCE

KYLE DICKMAN

How Los Alamos learned where space storms begin—and why forecasting them is the next frontier.

A few hours after the sun set on November 12, 2025, physicist Michael Henderson drove from his home in Los Alamos, New Mexico, toward the darker skies of Valles Caldera National Preserve an hour west. The night before, the Northern Lights had lit up New Mexico in a rare display of green and red. Henderson, a space scientist at Los Alamos National Laboratory, had seen none of it. That night, space-weather forecasters predicted an aurora that would rival that first brilliant show. Only it never materialized. "Kind of a dud," Henderson says, unsurprised but no less disappointed. "Space weather is a fantastically complex system. We just aren't very good at predicting it."

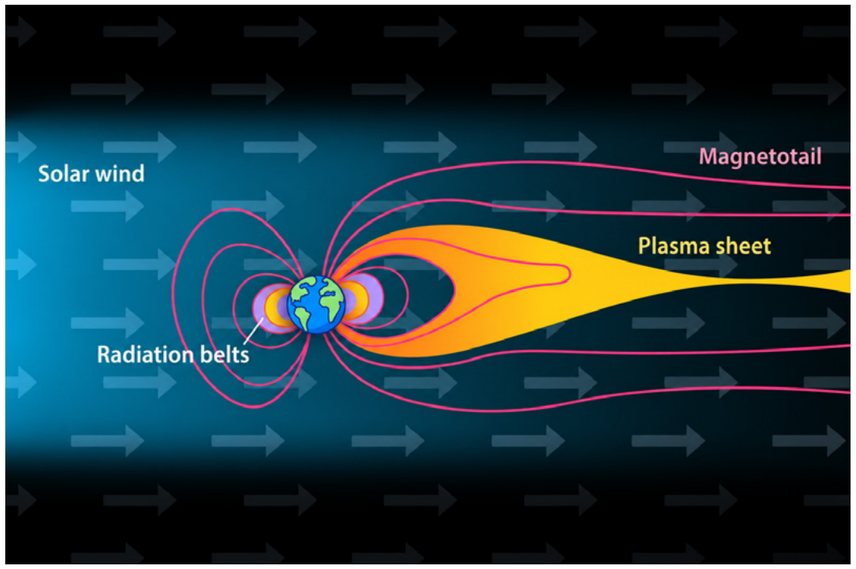
"SPACE WEATHER IS A FANTASTICALLY COMPLEX SYSTEM. WE JUST AREN'T VERY GOOD AT PREDICTING IT."

Aurora chasing may be a hobbyist's pursuit, but the same physics that make the night sky dance can also shut down the world's communications and navigation systems. Henderson focuses his work on the national and—increasingly—economic security implications of space. As a sector, space is growing faster than global gross domestic product. Last year, the global space economy topped five hundred billion dollars and is expected to approach one trillion within a decade. From banking and navigation to weather forecasting and farming, nearly every major industry depends on one or more of the 15,000 satellites now squeezed into Earth's crowded orbit. A single severe solar storm could cripple a huge percentage of those satellites and the essential services they enable. Despite all this, the world lacks a reliable warning system for space storms.

The aurora is just the visible part of space weather. When bursts of radiation and charged particles from the sun strike Earth's magnetic field, they set off electrical currents and magnetic disturbances that ripple through near-Earth space. Sometimes, those energetic particles bombard satellites. Occasionally, their effects reach the ground and disrupt electrical circuits, like the Carrington Event did when it set telegraph stations ablaze in 1859.

Many of the early insights into how space weather works came from the Vela satellites, which were launched into orbit in the early 1960s. The Velas carried Los Alamos–designed instruments to detect gamma rays, neutrons, and x-rays. Those instruments collected data continuously. In 1965, Los Alamos scientists dug into data from the satellites' electron and ion detectors and uncovered a feature in Earth's magnetic field that scientists didn't even know to look for.

Earth's molten iron core generates a magnetic field—a giant, tilted dipole—that shields the planet from solar radiation. The sun's hot outer atmosphere sends out a continuous stream of charged particles called the solar wind, and when that wind strikes Earth's magnetic field, it blows the field into a long tail on the planet's nightside. In the 1960s, when the Vela satellites crossed this magnetotail near the geomagnetic equatorial plane, they detected a pronounced peak in energetic electrons. In the center of the tail, where Earth's stretched magnetic field lines flatten and weaken, the Vela instruments revealed a dense sheet of plasma where charged particles collect: the plasma sheet, through which most of Earth's space weather flows.



When the solar wind strikes Earth's magnetic field, it stretches it into a long tail and energizes charged particles. Energy builds in the plasma sheet and, during magnetic reconnection, can be released—driving particles toward Earth or contributing to the supercharging of the radiation belts, with consequences for satellite communications worldwide. Understanding these processes has challenged Los Alamos researchers for decades.

Over the coming years, Los Alamos scientists dug deeper into the plasma sheet. In the mid-1970s, Lab scientist Ed Hones and others found that the plasma sheet thickens and thins during magnetic substorms. In this way, it acts as a reservoir of stored energy. When magnetic field lines in the tail reconnect, they fling charged particles earthward, where they collide with the upper atmosphere and ignite the aurora. This mechanism not only explained the lights Henderson chased in November but also space storms capable of disrupting communications and damaging satellites. "Space scientists had turned the magnetosphere into the largest plasma physics laboratory in the universe—for our instruments, it's just a few hours' flight away," Henderson says. He notes that work in this natural plasma laboratory has contributed to many other areas of research involving plasma, including fusion-energy efforts here on Earth.

"SPACE SCIENTISTS HAD TURNED THE MAGNETOSPHERE INTO THE LARGEST PLASMA PHYSICS LABORATORY IN THE UNIVERSE."

By the early 2010s, Los Alamos's space-science program reached across the solar system. It had built instruments for missions that studied the solar wind, probed the outer heliosphere, and even detected water plumes on a distant moon of Saturn. But closer to home, Lab scientists had turned their attention to another dynamic region of near-Earth space: the Van Allen belts, two radiation belts that arc between about 600 and 26,000 miles above the planet. For decades, satellites passing through or near these belts had suffered mysterious failures during geomagnetic disturbances: communications outages, unexpected charging events, even the total loss of spacecraft. Nobody understood why. Some believed the damage came from electrons that drifted slowly inward from the outer magnetosphere and gained energy as they approached Earth; others suspected more complex, local acceleration processes right inside the belts.

To find out what caused these failures, NASA launched two spacecraft called the Van Allen Probes directly into the belts in 2013. Onboard were Los Alamos–built electron spectrometers. Using high-resolution electron measurements, scientists found that solar storms dump excess energy into the magnetosphere, which in turn triggers the local acceleration of electrons right inside the belts. Within a few hours, local electrons can reach energies high enough to punch through satellite electronics like tiny missiles, crippling a spacecraft. "Geomagnetic storms can supercharge the radiation," Henderson says.

Los Alamos's discovery and extensive research on the radiation belts gave rise to ongoing Lab efforts like Radiation Belt Remediation, one of Henderson's primary projects. The idea is that maybe the electrons in the radiation belts can be removed before they reach energies that make them lethal projectiles. Normally, charged particles "drizzle" slowly out of the belts into Earth's atmosphere, shedding energy as they collide with air molecules. But after a major nuclear event in near space, high-energy particles can persist in the belts for years, making it nearly impossible to rebuild space infrastructure. "If someone ever created an artificial radiation belt, we'd want to get rid of it as fast as possible so we could start to rebuild," Henderson says. One way to do this, he believes, is to generate electromagnetic waves or deploy antennas in orbit that nudge particles downward faster, clearing the danger from the belts.

But implementing a viable remediation scheme has proved incredibly challenging, and there remains much work to be done on the natural systems, including predicting when large geomagnetic storms will develop. "We can see a solar eruption and say, 'something big might hit in two or three days—or maybe not.' We need to do better than that," Henderson says. "Every one of these advances, and dozens more, is another step in the right direction. But we're not there—not yet." ■



With this historical look back at some of Los Alamos National Laboratory's most significant achievements, *1663* magazine comes to a close.

For two decades, from 2006 to 2026, *1663* shared the science, technology, and engineering stories of Los Alamos: the major research initiatives, the technical accomplishments, the people and teams behind them, and the fundamental discoveries that expanded the boundaries of what is known. Its name honored the Lab's earliest days in service to the nation, when the outside world knew the secret wartime laboratory only by its mailing address: P.O. Box 1663, Santa Fe, New Mexico.

This final issue is both a farewell and a thank-you—to the readers who followed these stories, to the scientists, engineers, technicians, and staff who made them possible, and to everyone who helped bring them to the page. *1663* ends here, but the work it chronicled continues: asking hard questions, solving consequential problems, and advancing deterrence for the nation through Los Alamos science.

ISSN: 1942-6631

Printed on recycled paper

1663
Mail Stop A117
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

1663magazine@lanl.gov

Presorted Standard
U.S. Postage Paid
Albuquerque, NM
Permit No. 532



Ashley Pond is a community oasis in downtown Los Alamos. When the Laboratory was first established, technical labs and office buildings lined the pond's banks.

Los Alamos NATIONAL LABORATORY

NNSA National Nuclear Security Administration

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is managed by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy under contract 89233218CNA000001.
A U.S. Department of Energy Laboratory LA-UR-26-27891