Lawrence Livermore National Laboratory

September 2017

Science & Technology REVIEW

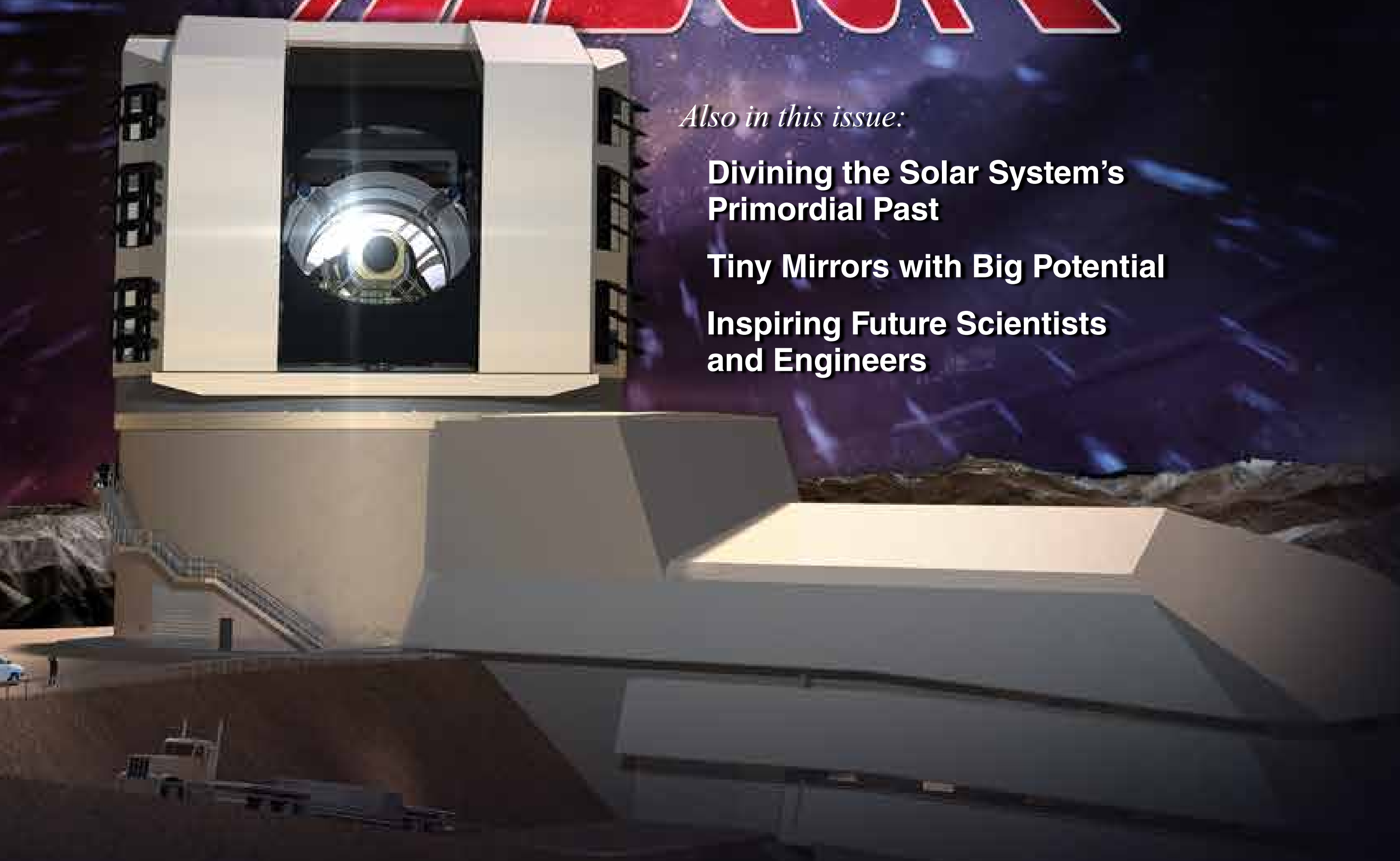
The Game-Changing Telescope

Also in this issue:

Divining the Solar System's Primordial Past

Tiny Mirrors with Big Potential

Inspiring Future Scientists and Engineers



About the Cover

The Large Synoptic Survey Telescope (LSST) promises to unlock mysteries of the universe in astronomical proportions. During its 10-year survey of the skies, this cutting-edge telescope is expected to make myriad unexpected discoveries and catalog billions of objects, from icy comets to stealthy planetoids, exploding stars, newborn galaxies, and everything in between. As the article beginning on p. 4 describes, Lawrence Livermore has made groundbreaking contributions to the multinational collaborative effort behind LSST, affecting how the giant telescope has been constructed and will be operated. The cover is an artist's rendering of LSST atop the Chilean mountain where construction is currently under way. (Image courtesy of LSST and the National Science Foundation.)

Cover design: Amy E. Henke

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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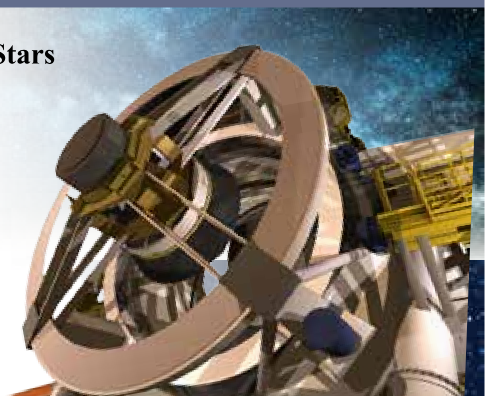

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Greenland Ice Sheet Responds to Climate Change

Researchers from Lawrence Livermore, the University of Vermont, Boston College, and Imperial College London analyzed marine sediment cores containing isotopes of aluminum (Al) and beryllium (Be), which are like a time capsule preserving records of glacial processes, and discovered that East Greenland experienced deep, ongoing glacial erosion over the past 7.5 million years. Appearing in the December 8, 2016, issue of *Nature*, their research reconstructed ice sheet erosion dynamics in the region over this timeframe. Team members in East Greenland are shown in the photo below (courtesy of the University of Vermont).

Cosmic rays continually bombard Earth and produce Al and Be isotopes in mineral lattices. The concentrations of these cosmogenic nuclides in rock, sand, and soil reveal the exposure history of the surface. Production rates and nuclide concentrations decrease exponentially within a few meters of the surface, so a covering of ice stops cosmogenic nuclide production in the underlying rock. Coauthor and Livermore scientist Susan Zimmerman used the Laboratory's Center for Accelerator Mass Spectrometry to analyze the isotopes found in the quartz sand from ice-rafted debris in sediment cores.

Analyzing these isotopes in sediment shed from the land and stored at the bottom of the ocean as marine sediment gave scientists insight into how Greenland responded to climate change in the past and how, in turn, it may respond in the future. "The East Greenland Ice Sheet has been dynamic over the last 7.5 million years," says lead author and University of Vermont scientist Paul Bierman. "Greenland was mostly ice-covered during the mid- to late Pleistocene. At major climate transitions, the ice sheet expanded into previously ice-free terrain, confirming that the East Greenland Ice Sheet has consistently responded to global climate change."

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More Efficient Catalysts with Nanostructured Materials

Lawrence Livermore materials scientist Juergen Biener and collaborators from Harvard University and Lawrence Berkeley and Brookhaven national laboratories found a way to make nanoporous gold alloys more efficient catalysts through restructuring. Such nanostructured materials hold promise for improving catalyst activity and selectivity, but until now little has been known about the dynamic compositional and structural changes that the system undergoes during pretreatment leading to efficient catalyst function.

Nanoporous gold can be used in electrochemical sensors, catalytic platforms, fundamental structure property studies at the nanoscale, and tunable drug release. The material also features high effective surface area, tunable pore size, well-defined conjugate chemistry, high electrical conductivity, and compatibility with traditional fabrication techniques. Ozone-activated silver–gold alloys in the form of nanoporous gold were used to demonstrate the dynamic behavior of bimetallic systems during activation to produce a functioning catalyst. In a reactant stream of methanol and oxygen, advanced in situ transmission electron microscopy and ambient pressure x-ray photoelectron spectroscopy revealed that major restructuring and compositional changes occurred along the path to catalytic function.

Researchers found an increased concentration of silver at the surface plays a key role in facilitating the catalytic function of the nanoporous gold, whereby the oxygen is more efficiently dissociated and made available for methanol oxidation. Biener, a coauthor of the research published in the December 19, 2016, online edition of *Nature Materials*, says, "Our results demonstrate that characterization of these dynamic changes is necessary to unlock the full potential of bimetallic catalytic materials."

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Model Yields Insights into Deposition Process

A team of Lawrence Livermore researchers developed a semiempirical, particle-based computer model for electrophoretic deposition (EPD) that will provide scientists and engineers with unprecedented insights into this widely used coating technique. The process uses an electric field to drive colloidal particles—that is, particles suspended in a liquid—from a solution onto a conductive substrate. Commonly used to apply paint to cars, EPD can be used to coat ceramics, metals, and polymers. New applications of EPD used with additive manufacturing are also being developed.

The team, led by principal investigator Todd Weisgraber, developed the model and ran different mesoscale simulations, changing the strength of the electrical field and the electrolyte concentration. Using a particle dynamics framework and run on the Laboratory's Vulcan supercomputing system, the model tracks every single particle—each about 200 nanometers wide—throughout the entire EPD process. The team's research is published in the December 20, 2016, issue of the journal *Langmuir*.

"This framework gives us more information than any model before and fresh insights that were previously inaccessible," says Brian Giera, the study's coauthor. "Within this particle dynamics framework, we were able to get really detailed information." The model can be used to better understand deposition kinetics and can be augmented to allow for virtually any type of material, extending the science to a broad range of applications. Giera adds, "The model is poised to take on a lot of questions. It gives us more predictive information to optimize the system."

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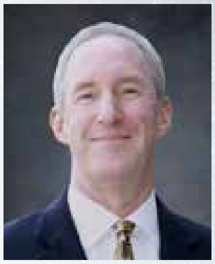
Commentary by Glenn A. Fox



From Shining Stars to Classroom Stars

As a child of the Apollo generation, I remember the excitement of the lunar missions. Sitting in front of the family TV and watching Neil Armstrong take the first steps on the Moon, returning to Earth, and splashing down in the ocean was a time when wonder and science first came together for me. The science of space—astronomy, astrophysics, planetary geology—continues to spark the imagination and enthusiasm of kids and adults alike.

Completing big, bold, and difficult scientific endeavors—whether landing on the Moon or the more modern and timely development of a next-generation telescope—requires the long-term scientific vision to anticipate and invest in such projects before anyone else is thinking about them, as well as the commitment to see them through. For instance, the groundbreaking Large Synoptic Survey Telescope (LSST), described in the article starting on p. 4, will not enter into full operations until 2023, but Lawrence Livermore had been contributing its expertise to the project since early in the undertaking. Building on our deep experience in constructing complex optical systems such as the National Ignition Facility, we are helping to build the largest and most advanced camera ever assembled, one that will be an integral part of LSST.

This effort, although still in progress, has already spun off other technological advances. For example, Livermore researchers have applied the technology allowing LSST's 27-foot-diameter primary mirror to gaze into space to create tiny CubeSat satellites, each no bigger than a stack of books, which now gaze from space to Earth. Once operational, LSST will give us a wider, deeper look at the sky than any ground-based telescope can, enabling investigations into dark matter and dark energy and the structure of our solar system, and even detecting potential collisions with Earth-crossing objects.

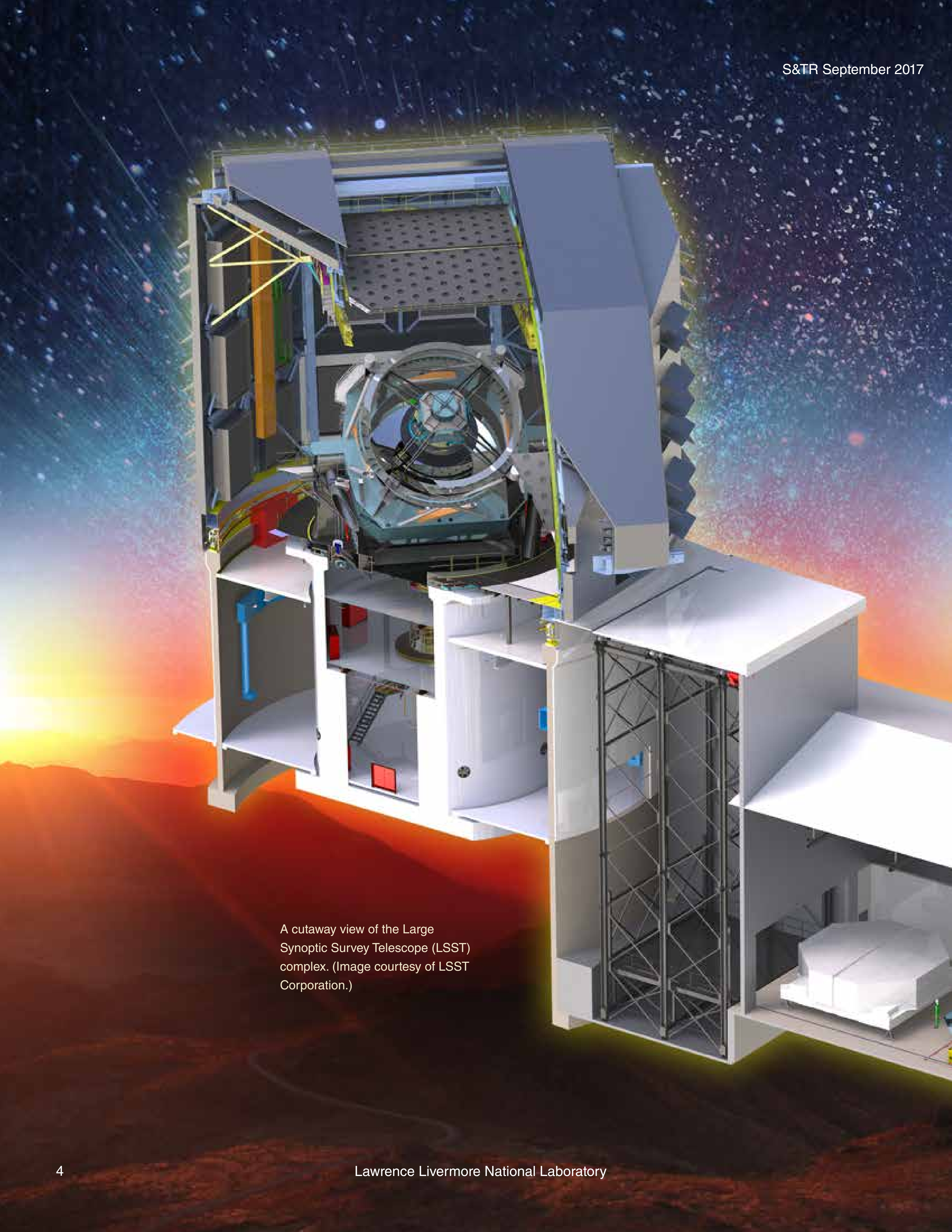
To develop the necessary technology for LSST or myriad other projects that fulfill the Laboratory's missions and the nation's needs, we must first lay the scientific groundwork for that technology. Such investigations can take years or even decades. Fortunately, Livermore researchers also excel at finding opportunities to make the most of these research endeavors. For instance, many of the same tools and techniques can be used to advance both cosmochemistry and nuclear forensics studies, and advances in one area can feed into the other. As described in the research highlight beginning on p. 12, Livermore's considerable nuclear forensics expertise is currently helping us gain new insights on the formation of our solar system.

The Laboratory Directed Research and Development (LDRD) Program is critical to investigating and understanding the fundamental science that underpins further technology and engineering advances. As with the LSST and CubeSat technology spinoffs, some LDRD projects can take us to places we hadn't initially imagined. For example, Livermore researchers, with LDRD funding, have developed an array of micromirrors with unprecedented speed and precision that is attracting interest from research fields as disparate as astronomy and self-driving cars (see article beginning on p. 16).

To deliver on our missions—and to maintain our leadership in worldwide science—we not only need to anticipate science and technology needs but also help ensure that we foster and sustain a talented, passionate, and diverse pool of scientific and engineering talent to perform the work. Just as we must lay the fundamental scientific groundwork for our technological applications, the Laboratory must lay its groundwork for future workforce needs by helping to spark and build an interest in science in young people through outreach efforts (see the article beginning on p. 20). Through student field trips to our Discovery Center and the Fun with Science programs, we hope to provide kids with their own "Apollo moments," where they can connect with and be inspired by the work we do—and hopefully see themselves being part of this science in the future. Finally, through our teacher training and summer student programs we aim to stoke the flames further.

Our people are the real strength of the Laboratory. With them, the sky's the limit.

■ Glenn A. Fox is associate director for Physical and Life Sciences.



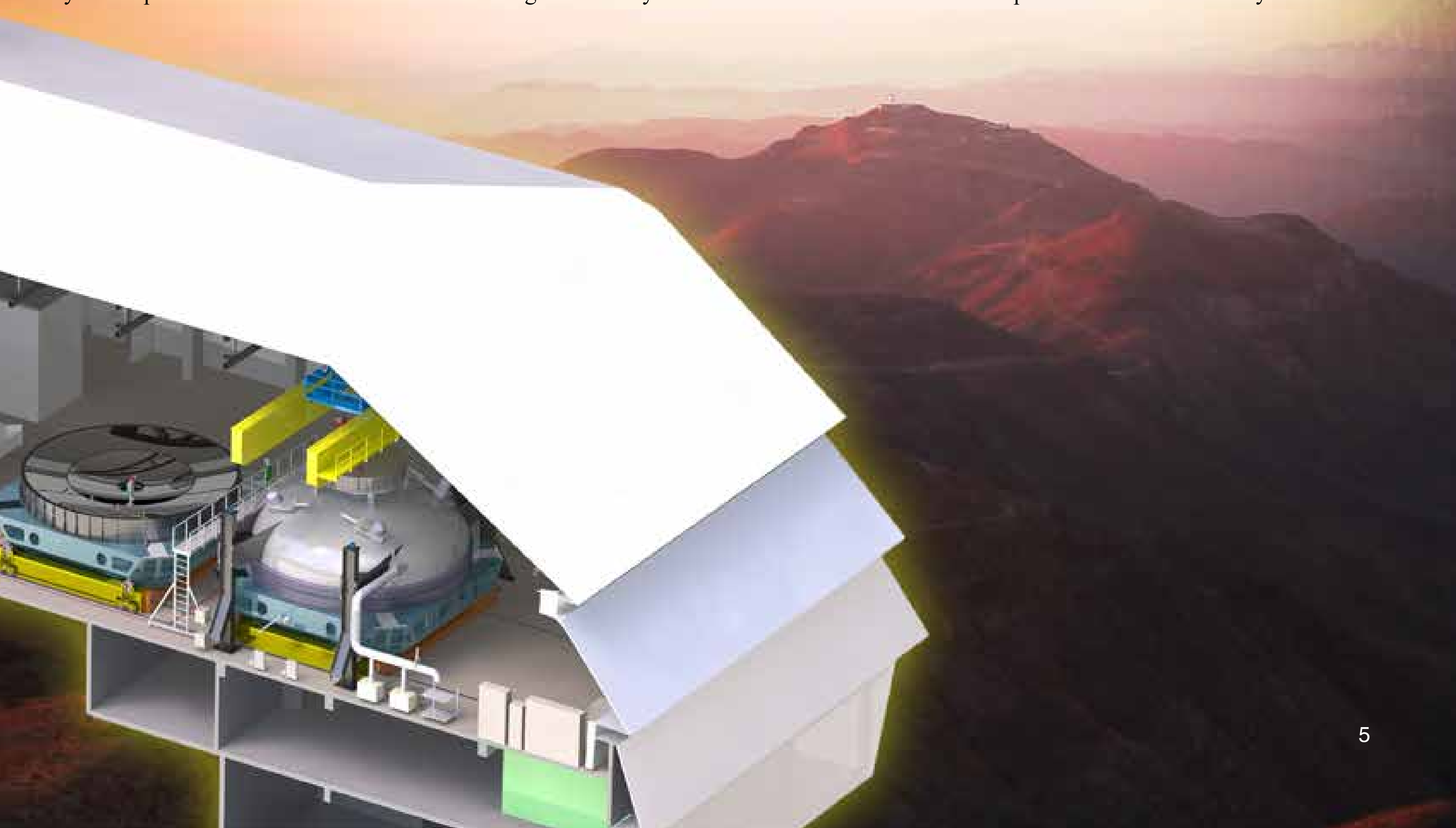
A cutaway view of the Large Synoptic Survey Telescope (LSST) complex. (Image courtesy of LSST Corporation.)

THE WIDEST, DEEPEST IMAGES OF A DYNAMIC UNIVERSE

The starry sky may not give the impression of much happening in the cosmos, but beyond our vision occur the wildest of events. A new telescope is set to reveal these intriguing phenomena to an unprecedented degree.

UNAIDED and under the darkest conditions, the human eye can see only about 9,000 stars around Earth. The Large Synoptic Survey Telescope (LSST)—looking at only half of the night sky—is expected to detect an estimated 17 billion stars and discover so much more over the course of a 10-year mission. However, without the crucial roles played by Lawrence Livermore, this major new telescope, now being constructed in Chile, might have only been science fiction instead of being on the verge of delivering game-changing science.

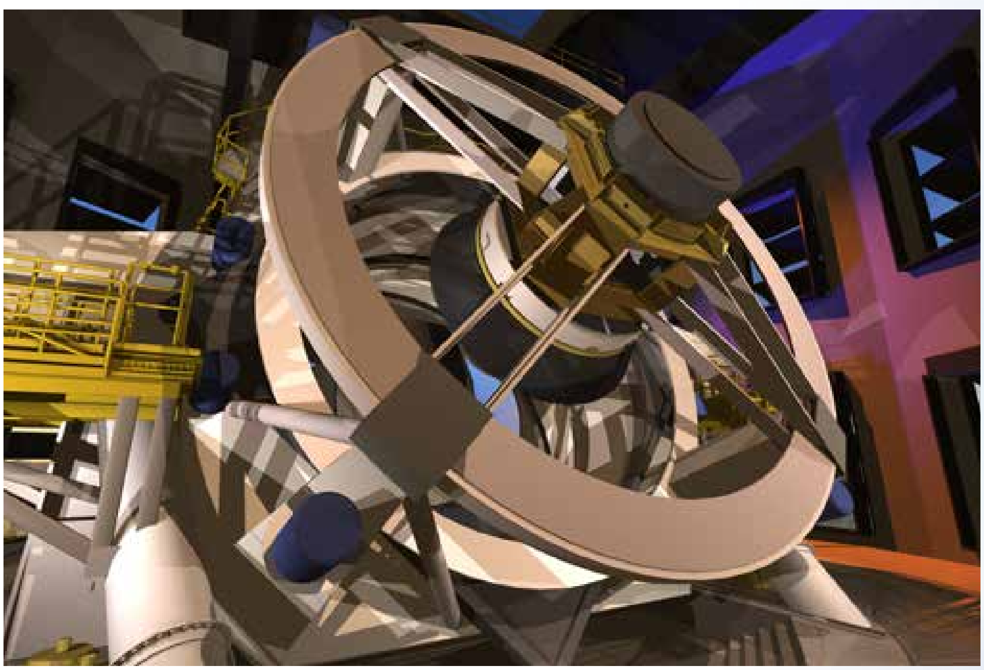
From icy comets to stealthy planetoids, exploding stars, newborn galaxies, and everything in between, billions of objects are expected to be discovered by LSST



during its survey of the universe. What also thrills stargazers and researchers alike is its great potential to yield a myriad of unexpected discoveries. LSST's core science areas are investigating the nature of dark matter and dark energy; cataloging moving bodies in the solar system, including hazardous asteroids; exploring the changing sky; and further understanding the formation and structure of the Milky Way.

Ground- and space-based telescopes are typically optimized to address one or two of these areas, resulting in designs that inhibit study in the others. However, the ingenuity of LSST's design, its grand size, and its use of groundbreaking technology promise to open the universe to exploration leaps ahead of what the telescopes of today can do. LSST director Steve Kahn, a physicist at Stanford University and the SLAC National Accelerator Laboratory, says, "Livermore has played a very significant technical role in the camera and a historically important role in the telescope design." Livermore's researchers made essential contributions to LSST's optical design, lens and mirror fabrication, the way LSST will survey the sky, how it compensates for atmospheric turbulence and gravity, and more. Kahn adds, "Livermore also plays a substantial role in the science of dark energy."

Livermore joins forces with a team of hundreds representing dozens of domestic institutions and international contributors from more than twenty countries. The consortium also relies on industry experts to fabricate components that have designs pushing well beyond current boundaries. LSST Corporation formed in 2002 and began privately funding the early development of LSST, including mirror fabrication and survey operations. The Department of Energy (DOE) funds camera fabrication, while the National Science Foundation funds the remaining telescope fabrication, facility construction, data management, and education and outreach efforts.

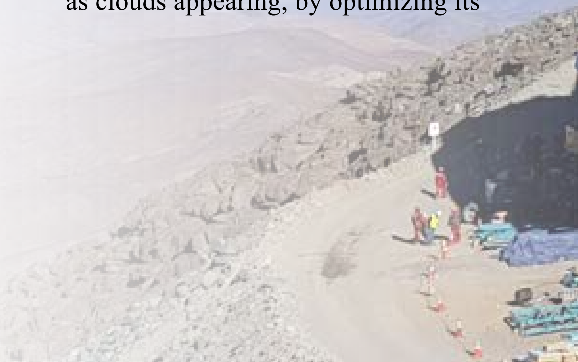


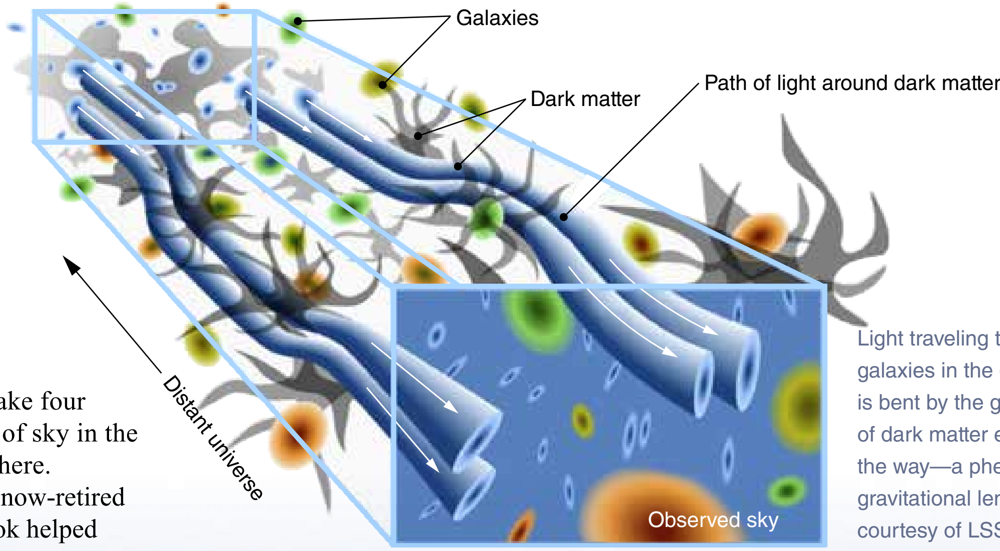
Despite its compact design, LSST weighs a massive 350 tons. Of this total, 300 tons comprise moveable parts. (Image courtesy of LSST Corporation.)

The telescope is scheduled to begin full scientific operations in 2023. The first stone of the LSST Summit Facility was laid in April 2015 on El Peñón, a peak 2,682 meters high along the Cerro Pachón ridge in the Andes Mountains and located 354 kilometers north of Santiago, the capital of Chile. Locations around the world were scrutinized to find the most suitable site. Chile—already a world leader as a site for modern mountaintop telescopes—won out by offering the best combination of high altitude, for less atmosphere to peer through; desolation, for less light pollution; dry environment, for fewer cloudy days; stable air, for less turbulence; and the infrastructure necessary for construction and operation.

The First Universal Motion Picture

Every night for 10 years, LSST will conduct a wide, deep, and fast survey comprising roughly 1,000 "visits" that together will canvas a third of the sky above the Southern Hemisphere. In each visit, the telescope will capture a pair of 15-second exposures before moving on to a new location. Taking back-to-back exposures of a single patch of sky will help eliminate erroneous detections, such as when cosmic rays strike the camera's detector. After finishing a visit, a neighboring part of the sky typically will be chosen to minimize slew time—the approximate 5 seconds that LSST will need to reposition itself and for vibrations to settle down to a level that will not impede image resolution. However, LSST can respond to sudden changes in surrounding conditions, such as clouds appearing, by optimizing its





Light traveling to Earth from galaxies in the distant universe is bent by the gravitational force of dark matter encountered along the way—a phenomenon called gravitational lensing. (Image courtesy of LSST Corporation.)

survey pattern on the fly and rapidly switching to a filter that provides more favorable viewing. Furthermore, for every spot visited, LSST will return an hour later to take another pair of exposures. Thus every three days LSST will take four images of every single patch of sky in the observable Southern Hemisphere.

In the early days of LSST, now-retired Livermore physicist Kem Cook helped develop the operations simulator, which schedules where the telescope will point for every exposure over the 10 years. Kahn says, "Cook's scientific interests were in time domain astronomy—looking at how things changed with time. How we sample the sky is key to the time history of all these exposures." Over 10 years, the telescope will generate 5.5 million individual images. When stitched together like individual movie frames, the images will yield what LSST's builders call "the first motion picture of the universe." In fact, the total image data produced will be the equivalent of 15,500 feature-length motion pictures on 35-millimeter film. This moving picture prowess will evolve astronomy from traditional static views of the universe to stellar time-lapse photography, like studying how a bird flies in real time instead of only looking at individual photographs.

Illuminating the Dark

In a galaxy far, far away is the preamble to a well-known science-fiction epic, but 20 billion very far-away galaxies is what LSST expects to view. Instead of the "dark side," the telescope will investigate the mysteries of dark matter and dark energy. A cosmic accounting of all the solids, liquids, gases, and other identifiable forms of matter does not even come close to estimates of the grand total of all matter in the universe. "Dark matter is about 95 percent of the total mass that we can infer exists in the universe," explains Michael Schneider, the physicist leading Livermore's LSST science efforts, which are funded primarily by the Laboratory Directed Research and Development (LDRD) Program and DOE's

Construction of LSST is well under way on the 2,682-meter El Peñón peak in the Andes Mountains of Chile, as shown in this photograph taken in May 2017. (Photograph courtesy of LSST Corporation.)

Office of Science. "Furthermore, all mass in the universe—dark matter and normal matter—accounts for only about a third of the total energy density. The other two-thirds is dubbed dark energy." Do dark matter and dark energy exist only in deep space? Or do they also exist in our solar system and even around Earth, as well? Do they help comprise our planet and our physical bodies? Such are the questions that researchers will seek to answer with LSST.

In addition, light from bright galaxies can be distorted by the gravitational force from dark matter caught in the line of sight. This gravitational lensing can be understood by measuring the shapes of galaxies. Schneider says, "LSST may be the final ground-based survey instrument built in our lifetimes to measure that effect with subpercent precision, map the mass in the universe, and thereby locate dark matter and dark energy and help figure out what they are."

Space Invaders and Cosmic Origins

Although mystery currently shrouds the composition of dark matter and dark energy, scientists understand all too well the compositions of hidden "space invaders"—objects on an intercept course with Earth. The wide, fast, and deep features of LSST make it unquestionably the most efficient way of identifying near-Earth objects (NEOs) whose orbits cross Earth's and so could one day strike our planet. The search for NEOs is the primary reason for the hourly revisits programmed into LSST's survey cadence. The time between the first and second pairs of images is enough to show differences revealing an NEO, which can then be tracked and its orbit determined. If LSST's 10-year mission is extended by a couple of years, the telescope could detect 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter. LSST could also provide 1 to 3 months of warning for those as small as 45 meters. Even an NEO with a diameter of less than 100 meters could impact Earth with the force of a nuclear bomb. Advance notice offers the time needed to defeat these otherworldly threats. (See *S&TR*, December 2016, pp. 16–19.)

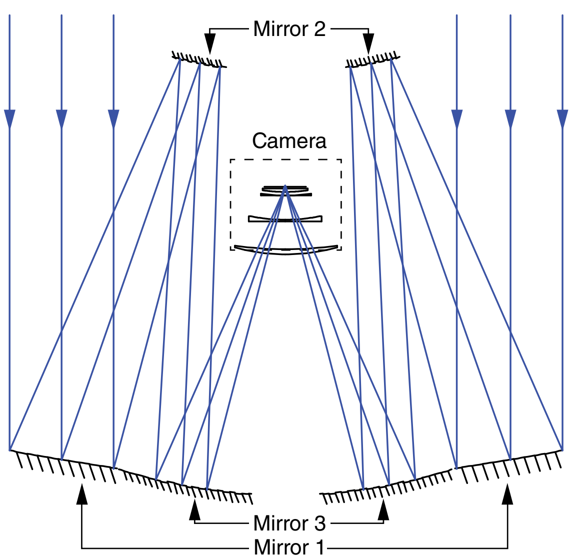
An important parameter of a telescope is its étendue, or "grasp," defined as the field of view multiplied by the surface area of the primary mirror. At 319 meters squared–degrees squared, LSST's étendue exceeds that of any current facility by more than a factor of 10. Such an enormous increase will lead to science opportunities never before possible.

Images taken with such great breadth, speed, and depth will capture fleeting astronomical events, possibly recording up to 4 million supernovas, for instance. By better recording objects in the solar system and the rest of the Milky Way and how they move, scientists will more clearly understand how Earth's solar system and galaxy formed. Putting these varied puzzle pieces in place could unravel the mysteries surrounding the universe, including Earth's cosmic origins.

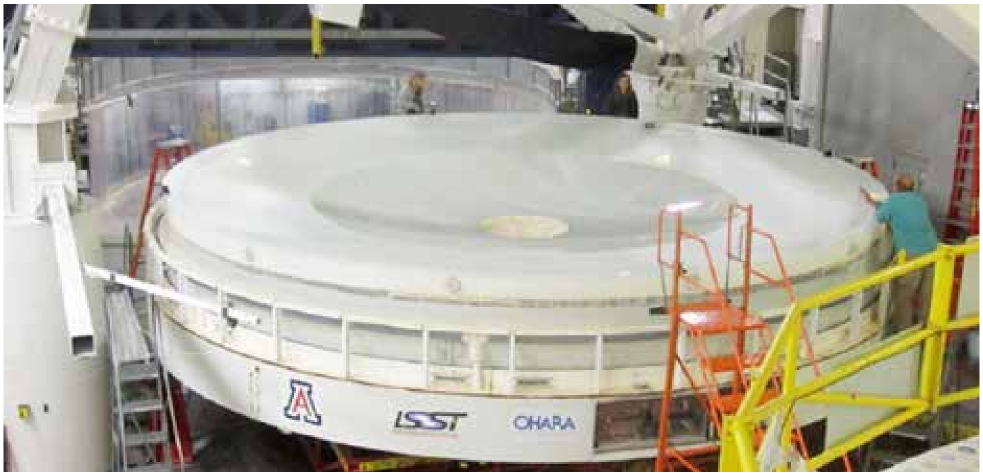
Beyond Galileo

LSST must move like a racecar among telescopes to accomplish such science goals—a great challenge considering that the camera by itself weighs 3,060 kilograms. The entire moveable structure of the telescope, including the camera, tips the scales at 272,000 kilograms. To achieve its speedy performance, LSST's design needed to be as compact as possible. This contradicts the conventional wisdom that to see wider and deeper into space, a telescope and its optics must be built as big as possible. Materials and fabrication limitations alone would prohibit the type of telescope—a long tube capped by a lens at each end—that has been widely used ever since Galileo used one to first identify Jupiter's moons. Moreover, the machinery to wield such a telescope would be colossal. Moving such a behemoth between locations and waiting for the vibrations to subside would be measured in hours instead of seconds, rendering the telescope useless for any science dependent on rapid scanning. In short, a breakthrough in telescope design was needed.

The breakthrough began in 1998, a year after the first paper positing the existence of dark energy was published, when Roger Angel of the University of Arizona proposed a three-mirror design with a primary-mirror diameter of roughly 6 meters. As the potential for additional capabilities became more apparent, this diameter was increased to 8.4 meters. Kahn notes, "A lot of refinements radically changed the early design concept, and



As shown in this ray diagram, light entering the telescope reflects between three mirrors and then is focused through three lenses and a filter before striking the camera's detector. (Image courtesy of Lynn Seppala.)



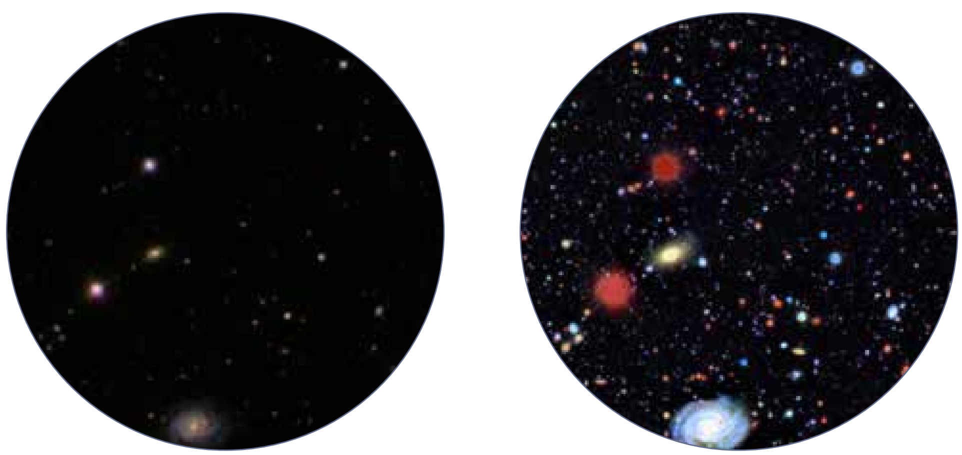
The photograph shows one of LSST's many design innovations—an integrated mirror monolith with a dual optical surface combining the primary and tertiary mirrors. (Photograph courtesy of LSST Corporation.)

Livermore physicist Lynn Seppala played a very important role. A lot of his ingenuity went into it." Seppala, now retired, was tasked with evaluating Angel's optical design to determine whether the sizes, shapes, and placements of the optical elements—lenses, mirrors, and filters—would meet the demands of LSST. He determined the design would theoretically work but would be essentially unbuildable because of its complexity, size, and lack of robustness. More iterations followed. "I wanted to make everything as foolproof as possible," says Seppala. He felt ease of manufacture was essential to LSST's optical design. "How are you going to test it? And how are you going to certify it? My strategy was to carry out, with each design iteration, a set of simple fabrication tests for all of the lenses, the three-mirror telescope without the camera, and the assembled three-lens camera corrector. Simplifying these tests would increase reliability both during fabrication and in assembling the camera and telescope."

A groundbreaking approach that further simplified the optics and drastically reduced the length of the telescope came when Seppala helped optimize a design where the primary mirror (M1) and the tertiary mirror (M3) were combined into the same piece of glass, eliminating a set of support and alignment structures. The weight-savings appeal of this dual optical surface eventually inspired new designs, which have been patented by the Laboratory. Miniature versions of this technology can be found in tiny CubeSat satellites. (See *S&TR*, April/May 2012, pp. 4–10.) Seppala also emphasized keeping the 3.4-meter-diameter secondary mirror (M2) as spherical as possible for ease of manufacture without sacrificing performance. The enormous size of this mirror can be understood by noting that the secondary mirror of any existing telescope could fit easily inside the center hole of M2. LSST's giant camera also conveniently fits inside the center hole, greatly simplifying its mounting.

Because the camera is so sensitive, its detector is sealed inside a vacuum chamber, and three lenses correct the path of inbound light from the mirrors before striking the detector. At a diameter of 1.55 meters, the first lens through which the light passes is also the largest high-performance optical glass lens ever built. The third lens (L3) also acts as the vacuum chamber window. Between the second lens and L3 will fit one of six filters, which can be switched in and out by the armature of a fast-acting carousel, similar to the mechanism that changes records in an old-fashioned jukebox. Each filter has an individualized coating that allows through only light in a specific wavelength range. By uniformly scanning the sky with each filter, LSST will permit multicolor analyses.

Whereas the mirror coatings must reflect as much light as possible and the filter coatings must exclude all but specific bands of light, LSST's lenses have antireflection coatings to maximize the amount of light passing through them. Fused silica, an amorphous form of quartz, is the glass used to make M2 and all the lenses and filters. A special spin-casting process was used to create a single piece of honeycomb-backed



The dramatic improvement in stargazing capabilities that LSST will enable is seen in this side-by-side comparison of the same sector of space revealed by (left) the recent Sloan Digital Sky Survey and (right) in a simulated LSST photograph. (Images courtesy of LSST Corporation.)

borosilicate glass, which was then polished into the shapes of M1 and M3. This approach reduced overall weight by 90 percent over conventional methods, making the telescope lighter and speedier to maneuver. This lightweight, compact design allows the mirrors and camera to be more easily and safely removed, minimizing down time for maintenance.

Wide and Deep

A telescope's field of view determines how much of the sky it can see. The entire sky from horizon to horizon encompasses a 180-degree field of view. A full Moon is only 0.5 degrees wide, but ground- and space-based telescopes typically have a field of view that is only a fraction of this lunar width. LSST, in contrast, boasts a gigantic 3.5-degree field of view, capturing an image area equivalent to 49 Moons. Needing fewer images to capture the entire sky speeds up the survey. LSST will also collect more light in less time than other telescopes, enabling viewing of objects as faint as 24 on the astronomical magnitude scale—roughly 10 million times dimmer than what is detectable by the unaided human eye. By combining images, LSST can reach even deeper, to a magnitude of 27. By comparison, relatively bright Saturn registers 1 on this scale, the stars of the Big Dipper 2, and the moons of Jupiter 5. The limit for the Hubble Space Telescope is a magnitude of 31, partly because of its orbit in space. Although able to detect dimmer objects than LSST can, Hubble has a very narrow field of view, equivalent to only a fraction of a full Moon.

Although Hubble does not have to contend with Earth's atmosphere, LSST faces atmospheric disturbances that threaten to drastically reduce image quality, as well as changes in environmental conditions and the shifting pull of gravity as the massive mirrors change positions. One way Livermore strove to minimize such effects was by drawing on its experience in adaptive optics (AO), a technique the Laboratory helped pioneer. (See *S&TR*, September 2014, pp. 4–12.) Another optics innovation incorporated into LSST is an active optics system that Livermore researchers developed in collaboration with the National Optical Astronomy Observatory. In this system, the reflective surface of all three mirrors is finely tuned by networks of actuators mounted on the backs of the mirrors. By slightly changing a mirror's shape, the actuators compensate for distortions in light caused by the small deflections of mirror surfaces that arise from changes in temperature or gravitational pull. In short, AO and active optics are key to LSST achieving its goals.

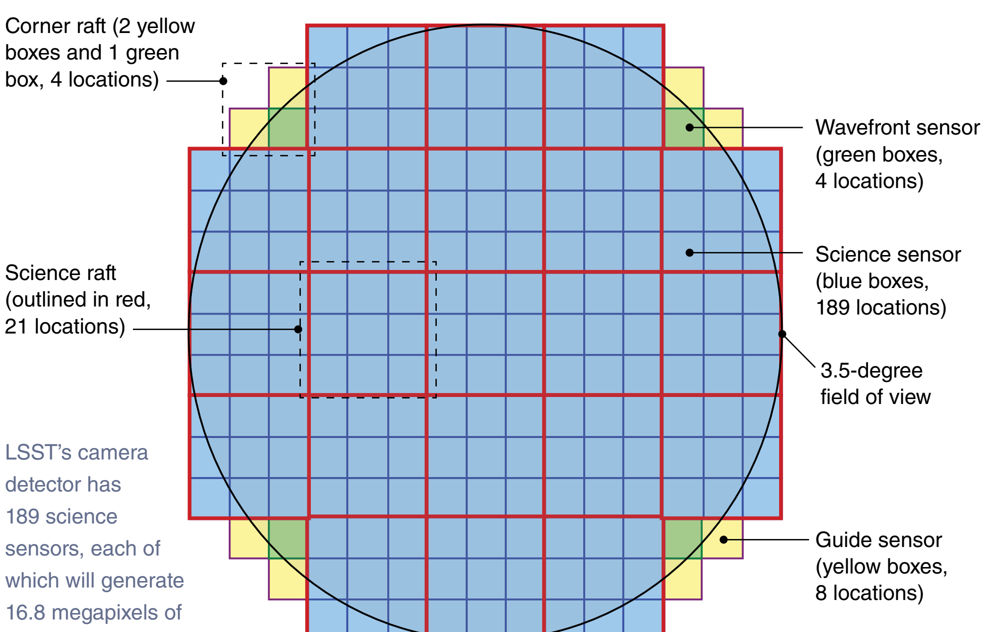
On the Shoulders of Giant Optics

The Laboratory is lending its optics expertise in other areas, as well. Livermore engineer Scott Winters, the optics subsystems manager for the LSST camera, states, "Livermore has a history of building complex optical systems, the latest being the National Ignition Facility (NIF). From fabrication, coatings, assemblies, and precision cleaning to other aspects, we're able to harvest this knowledge and apply it directly to the camera's optical systems. In short, LSST is getting years and years of experience and lessons learned from the Laboratory."

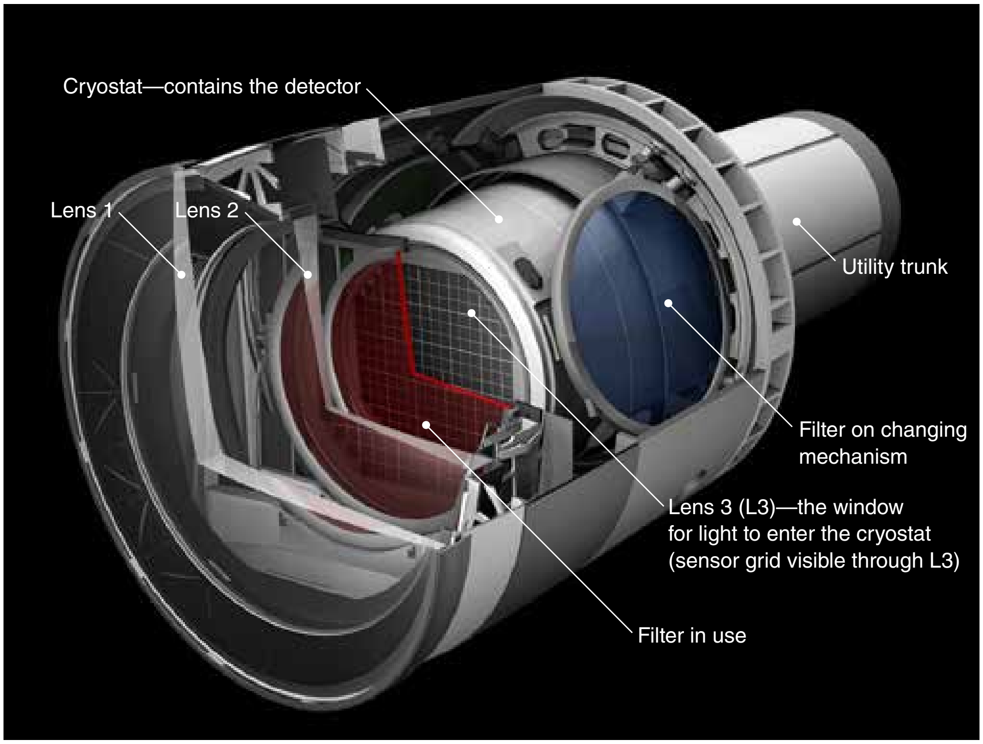
Livermore personnel led the procurement and delivery of the camera's optical assemblies, which include the three lenses, and six filters, all in their final mechanical mount. Livermore focused on the design and then delegated fabrication to industry vendors, although the filters will be placed into the carousel interface mount at the Laboratory before being shipped off to SLAC for final integration into the camera. Partnering with industry has been the approach taken to build NIF and the Laboratory's other large laser systems. Winters states, "LSST is all about leading-edge technology, including the world's largest camera, so it's an exciting project. We're able to do amazing things by engaging various people in cutting-edge work. This is a great win–win for everyone."

Super-Sensitive Sensors

SLAC is managing subcomponent integration and final assembly of the $168 million camera, which is currently over 60 percent complete and due to be finished by 2020. Livermore engineer Vincent Riot, interim project manager of the camera, says, "Many challenges come with making the largest camera in the



LSST's camera detector has 189 science sensors, each of which will generate 16.8 megapixels of image data.



With a maximum diameter of 1.65 meters, a length of 3.73 meters, and a mass of 3,060 kilograms, LSST's camera will be the largest ever made. (Image courtesy of LSST Corporation.)

world." The camera's detector is a bee's-eye mosaic of 189 ultrahigh-purity silicon sensors, each 100 micrometers thick. Each captured image is 4,096 by 4,096 pixels in size, or 16.8 megapixels in all. The entire detector thus delivers a combined pixel count of 3.2 gigapixels. In each corner of the detector are a wavefront sensor and two guide sensors, which ensure image quality by monitoring surrounding conditions and feeding back data that drive corrective measures, such as with the active optics system. Riot explains, "The wavefront and guide sensors must be sensitive to a very broad range of wavelengths, from deep ultraviolet to infrared, and must have very low noise and be very flat."

After light circuits its way through the optics, an image forms on the detector's 63.4-centimeter-diameter focal plane. The compactness of the telescope's optics makes the focus very unforgiving. A blurry image could result if any part of the detector surface is misaligned to the incoming light by more than 11 micrometers—approximately one-fifth the diameter of a human hair. The camera's sensors are charge-coupled devices, which create images by converting the incoming light (photons) into electrons. For this reason, the vacuum vessel that houses the camera is cryogenically cooled to an operating temperature of –100 to –80 degrees Celsius. This cooling has twin benefits—preventing overexposure defects, which tend to occur when such sensors are operated at warmer temperatures, and reducing signal noise from various sources. This improvement allows electrons to be more accurately counted and therefore produce the best images possible.

Petabyte Free-for-All

Each 3.2-gigapixel image will be saved as an image file roughly 6 gigabytes large. Because LSST needs only 2 seconds to read out raw data between exposures, the telescope will amass roughly 15,000 gigabytes of image data each night. Compounding this over 10 years of operation yields a total of 60 petabytes (10^{15} bytes). The images compiled in a single visit will be immediately compared, and if a difference is found, suggesting some event, an alert will be automatically issued within 60 seconds. Each night, LSST is expected to detect about 10 million such events. Single images and catalogs of images will be frequently streamed online, and the LSST computational system will do more advanced processing, such as time-lapse movies. Much of this imagery will be made available for free so that the public can learn about discoveries in near real-time and participate in "citizen science" opportunities.

Schneider explains, "The data science aspect of LSST is highly important. Rather than study one object at a time, which was the astronomy model of the past, LSST is actually statistical analysis conducted on a large, complicated dataset, and to do the really big science requires thinking about algorithms and computing in a different way than astronomers are used to doing." LSST's immense repository of data will not only drive research in new ways but also necessitate all-new studies on how to better analyze tremendous amounts of data. Livermore's wide-ranging contributions have elevated LSST to the forefront of science and technology. Soon LSST will deliver the promises of world-changing astronomy and a clearer understanding of how we fit into this wide, deep, fast universe of ours. Who knows where this journey will take us?

—Dan Linehan

Key Words: active optics, adaptive optics (AO), dark energy, dark matter, data science, dual optical surface, étendue, field of view, gigapixel camera, Large Synoptic Survey Telescope (LSST), National Ignition Facility (NIF), near-Earth object (NEO), optical design, spin-cast mirror, telescope, ultrahigh-purity silicon sensor.

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Unlocking the History of the Solar System

The nuclear detectives at Livermore were suspicious. Samples cannot lie, but the stories told by these particular materials raised too many questions. One sample after another from crustal rocks and mantle reservoirs gathered during the Apollo lunar missions clocked in at a narrow range of ages, between 4.30 and 4.38 billion years old. This surprising result was found no matter where the astronauts collected samples and no matter what isotope ratios the Livermore sleuths measured—rubidium-87/strontium-87, samarium-147/neodymium-143 ($^{147}Sm/^{143}Nd$), samarium-146/neodymium-142 ($^{146}Sm/^{142}Nd$), lutetium-176/hafnium-176, or lead-207/lead-206.

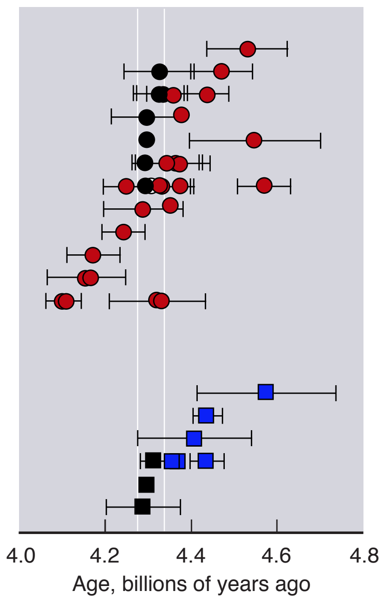
The theorists said those results could not be right. Some of the rocks had to be much older, because the Moon could not be that young. Moreover, the Moon was thought to have formed over a far longer period. Perhaps the astronauts failed to collect samples in locations where the oldest rocks lay. Or perhaps the theories are wrong. Livermore's 20 years of work measuring the ages of these lunar samples, summarized in a 2014 paper, points the finger at the latter possibility. Lars Borg, a chemist in Livermore's Nuclear and Chemical Sciences Division, says, "It's difficult to see how all of the different events recorded by the Moon rocks could have essentially the same age unless they all reflect the formation age of the Moon."

Planetary geologists are now trying to reconcile Livermore's findings with a revised theory, first formulated in the 1970s, of how Earth's Moon developed. According to this origin story, the Earth arose when dust orbiting the Sun began to accrete into solid clumps, then into larger bodies called planetesimals, and finally into Earth itself. Later, some other large body approximately the size of Mars collided with the Earth. Superheated rock and dust scattered, and then re-accreted, forming the Moon in Earth's orbit. Accretion of the Moon is thought to have produced enough heat to completely melt it. Computer modeling suggested that cooling of this ocean of magma was fairly rapid—lasting only a few million years—and resulted in a sequence of rocks in the lunar crust and mantle of approximately the same age. These rocks include the white crustal rocks that can be seen from Earth, as well as areas where dark basaltic rocks form the flat, smoother surfaces of the Moon called "mares," or seas, by Galileo.

If the above theory is correct, then all rocks thought to represent the first solidification products of the lunar magma ocean should yield roughly the same age. The problem is that ages measured since the 1970s span a range of 4.22 billion to 4.56 billion years ago, suggesting that either the model or the ages are incorrect. Most scientists argue that all but the oldest ages are incorrect. However, the detailed chronologic investigations performed by the Livermore team using newly developed techniques to precisely date individual samples with confidence indicated that all the samples solidified within a narrow window of time. If these rocks represent the solidification products of a primordial magma ocean, then they record the age of the Moon. The scientific debate continues, but Livermore's contribution to the evidence has significantly stirred the pot.

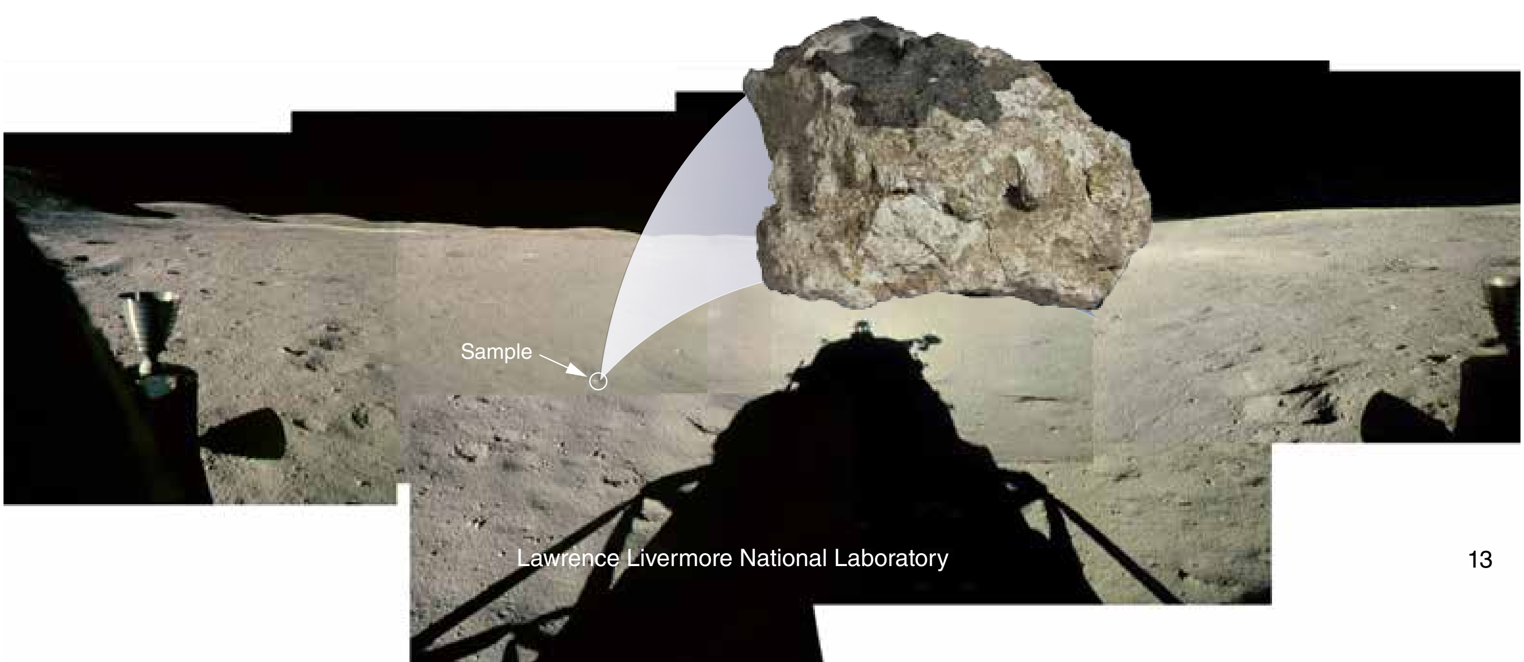
Cosmochemical Forensics

The radioactive decay of isotopes of certain elements provides scientists with a powerful tool—the ability to measure the age of a material anywhere from seconds to billions of years old. By measuring the abundances of parent and daughter isotopes in rocks and minerals with extremely accurate mass spectrometers, Livermore scientists can measure the age of planetary materials with a margin of error of less than 1 percent. Thus, the ratio of a gradually decaying radioactive parent isotope such as ^{147}Sm to its daughter isotope ^{143}Nd can be used to uniquely pinpoint the time billions of years ago that a rock solidified. At Livermore, these tools serve a dual role, supporting both cosmochemical research and nuclear forensic capabilities. Nuclear forensics is central to the Laboratory's



A Livermore cosmochemistry team led by Borg measured the ages of lunar crustal rocks using isotope ratios in samples collected by several Apollo missions. Instead of observing the long range of ages reported in the literature (red and blue symbols) indicating a lengthy lunar evolution, they found all the samples fell within a narrow band (white vertical lines) of between 4.30 billion and 4.38 billion years old (black symbols).

The Apollo 16 lunar lander took this composite photo on the Moon. A sample studied by Lars Borg and the cosmochemistry team at Livermore was retrieved at the location indicated. (Photographs courtesy of NASA.)



security missions, and cosmochemical work is key to developing techniques to measure isotopes that can be used to provide clues to the origin of illicit nuclear materials that might be diverted for use in weapons of mass destruction. In fact, many of the same systems used for cosmochemical research also apply to constraining the origins of nuclear forensics samples.

Borg explains, "In the 1980s, the Laboratory hired academically trained cosmochemists with expertise in mass spectrometry to contribute to the nuclear test program. They found that neutron reactions taking place in these tests were also relevant to cosmochemistry." As the Laboratory developed its nuclear forensics capability, a world-class cosmochemistry capability also came about. This cosmochemistry group began to unravel the history of the solar system, the ages when the planets formed, and the relationship of meteorites to the solar system's primordial matter. Thanks to decades of funding from NASA and Livermore's Laboratory Directed Research and Development Program, Livermore has become one of the world's foremost centers of research on the origin and evolution of the solar system, including Earth. Livermore researchers have studied samples relating to the age of the Moon and the timing of lunar impact basins, the age of volcanic activity on Mars, the evolution of the Martian atmosphere, the timing of Martian crust and mantle formation, and the sources of materials that contributed to the dust and gas that later condensed forming the Sun, planets, asteroids, and comets of our solar system.

Geological Cousins?

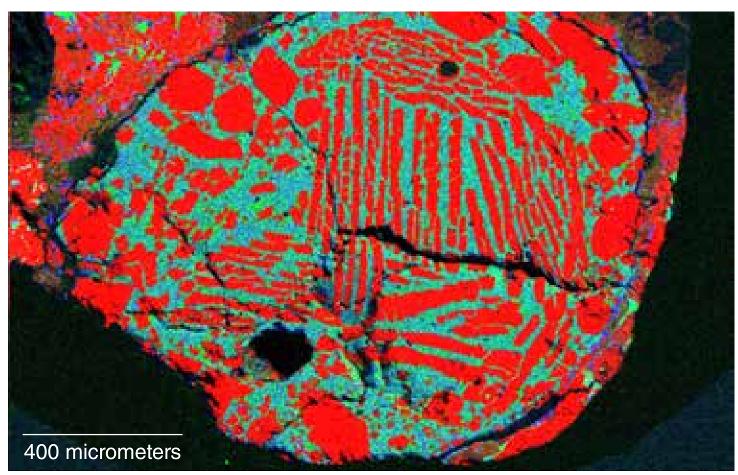
The Livermore cosmochemists excel at throwing doubt on long-established hypotheses. A common assumption among planetary geologists, for example, is that the composition of the Earth is equivalent on average to a common variety of stony meteorite called chondrites. Thousands of these meteorites have been found on Earth, and scientists assume their compositions reflect that of the solar system's primordial rocky matter from which Earth and the other planets formed. Then, beginning in about 2008, investigators elsewhere found that the neodymium-142/neodymium-144 ratio in crustal Earth rocks was higher than in chondrites by about 20 parts per million.

Theorists began suggesting that the early Earth was formed from a different reservoir of material than chondrites, or that Earth was enriched in material with a higher Sm/Nd ratio than chondrites, or that a hidden reservoir of material existed within the Earth. All of these theories, although equally plausible, lacked any supporting evidence. In early 2017, a group of Livermore researchers including Borg developed techniques to measure several other stable Nd isotope ratios in various chondrites. The team found that the stable isotopes of Nd were different in chondrites than in Earth, suggesting that terrestrial Nd derived from a slightly different proportion of nucleosynthetic sources than the Nd in chondrites.

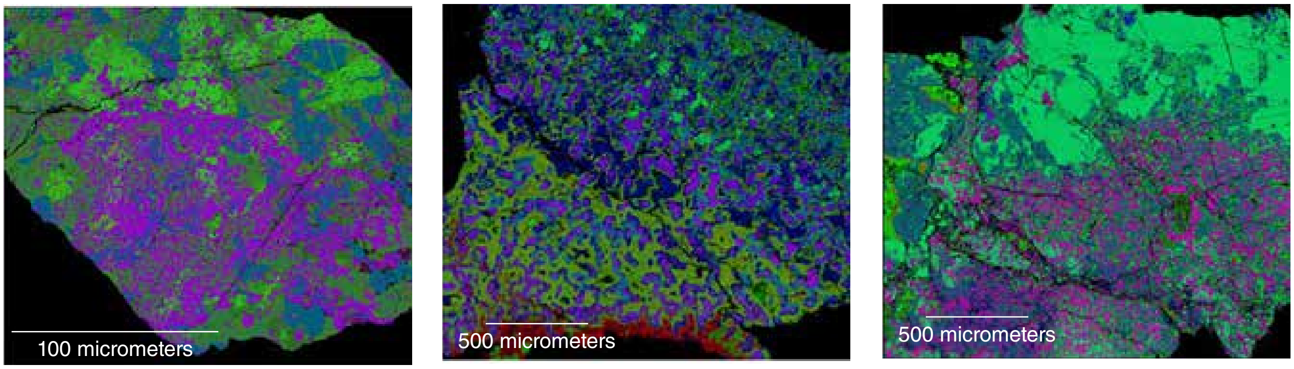
Heavy elements form through nucleosynthetic processes in the cores of giant stars and when stars explode in a supernova, ejecting the building blocks of new stars and planets. Each type of condition produces material with an identifiable isotopic signature. (See *S&TR*, July/August 2014, pp. 12–14.) Livermore's research suggested the Earth formed from material that was slightly richer in components from giant stars than in supernova material. Thus, the protoplanetary molecular cloud from which the solar system formed need not have been perfectly uniform in composition—material closer to the Sun could have had more giant star–derived Nd, whereas chondritic meteorites forming farther from the Sun would contain a higher proportion of material from supernovae. No special events were needed to alter Earth's mix. Instead, the protoplanetary molecular cloud simply had to remain heterogeneous during condensation of the first solids. Livermore's findings are again forcing a rethinking of current notions. Borg summarizes, "We are trying to provide the physical constraints by which the average composition of bulk chondrites represents the composition of individual planets."

Many Talents under One Roof

Livermore draws on the talents of many world-class cosmochemists—both on the staff and as visiting scientists—as well as exceptional technological capabilities. Borg states, "What makes us unique in the field is that we have the most relevant technologies in one building, as well as the people working in these laboratories under one roof who can solve various aspects of many problems. Teamwork gives us an advantage." Livermore's



The chondrule shown, found in a chondrite meteorite, was analyzed by Livermore cosmochemists. These particles are thought to be the first silicates to form in the solar system, possessing isotopic compositions characteristic of the earliest solar nebula. (Red, green, and blue indicate magnesium, aluminum, and calcium, respectively.)



These false-color microphotographs show examples of calcium aluminum–rich inclusions that Livermore's cosmochemistry team measured for traces of tellurium. The team searched for a radioactive tin isotope that might support the hypothesis that the solar system formed when a supernova caused the collapse of the protoplanetary molecular cloud. (Red, green, and blue represent magnesium, calcium, and aluminum, respectively.)

capabilities include several forms of mass spectrometry—inductively coupled plasma, thermal ionization mass spectrometry, and resonance ionization mass spectrometry (see *S&TR*, January/February 2017, pp.19–22). The Laboratory also used its Instrument Development Program funds to acquire a nanometer-scale secondary ion mass spectrometry (nanoSIMS) device, one of less than two dozen such devices in the world today. NanoSIMS enables Livermore researchers to measure isotope concentrations in submicrometer-sized parts deep inside a sample. A next-generation inductively coupled mass spectrometer is also due in September 2017.

Since coming to the Laboratory after time at NASA and the University of New Mexico, Borg has guided research addressing questions that reach ever farther out into space, even to the search for the perturbations that triggered the solar system's beginning. Borg, Gregory Brennecka—a former Livermore postdoc now at the University of Münster in Germany—and others recently developed a method for measuring tellurium-126 (^{126}Te) in calcium aluminum–rich inclusions (CAIs), particles thought to be the first solids to form in the solar system. Because ^{126}Te is a decay product of tin-126 (^{126}Sn), which forms only in supernovae, its presence in CAIs would support a decades-old hypothesis that a nearby supernova triggered the gravitational collapse of the molecular cloud that formed the solar system. In 2017, Brennecka, Borg, and colleagues reported a new method for detecting ^{126}Te at parts-per-million concentrations, or 30 times more sensitive than prior techniques. Finding no evidence for ^{126}Sn in the samples they studied, Borg and his team again cast doubt on long-established hypotheses. In addition, the scientific community now had a new way to continue the search.

Borg sums up why this research excites him: "What is really cool about this work is that we're looking at many different aspects of planetary formation, and it is painting a broad picture of how everything works. We're slowly answering the question, How did the solar system evolve?"

—Allan Chen

Keywords: calcium aluminum–rich inclusion (CAI), chondrite, cosmochemistry, inductively coupled plasma mass spectrometry, Laboratory Directed Research and Development Program, meteorite, nanometer-scale secondary ion mass spectrometry (nanoSIMS), nuclear forensics, planetesimal, resonance ionization mass spectrometry, nucleosynthesis, solar system evolution, thermal ionization mass spectrometry.

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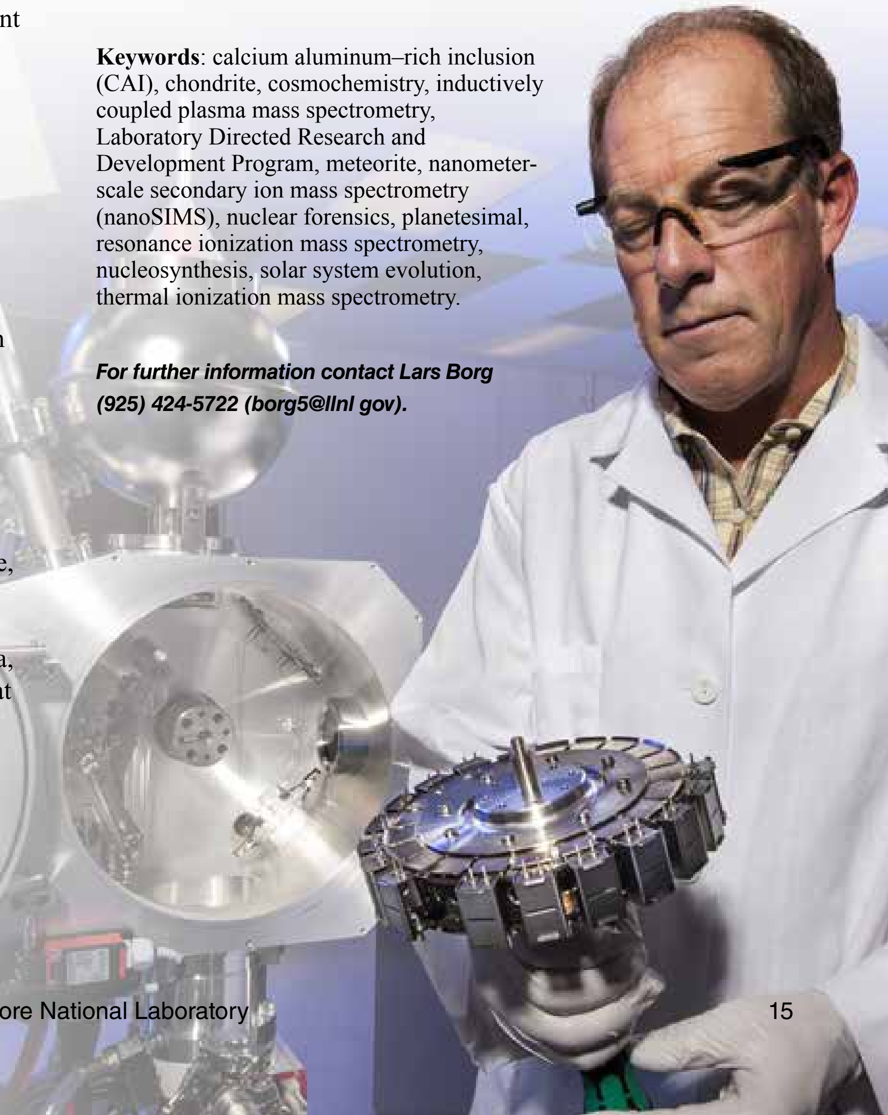
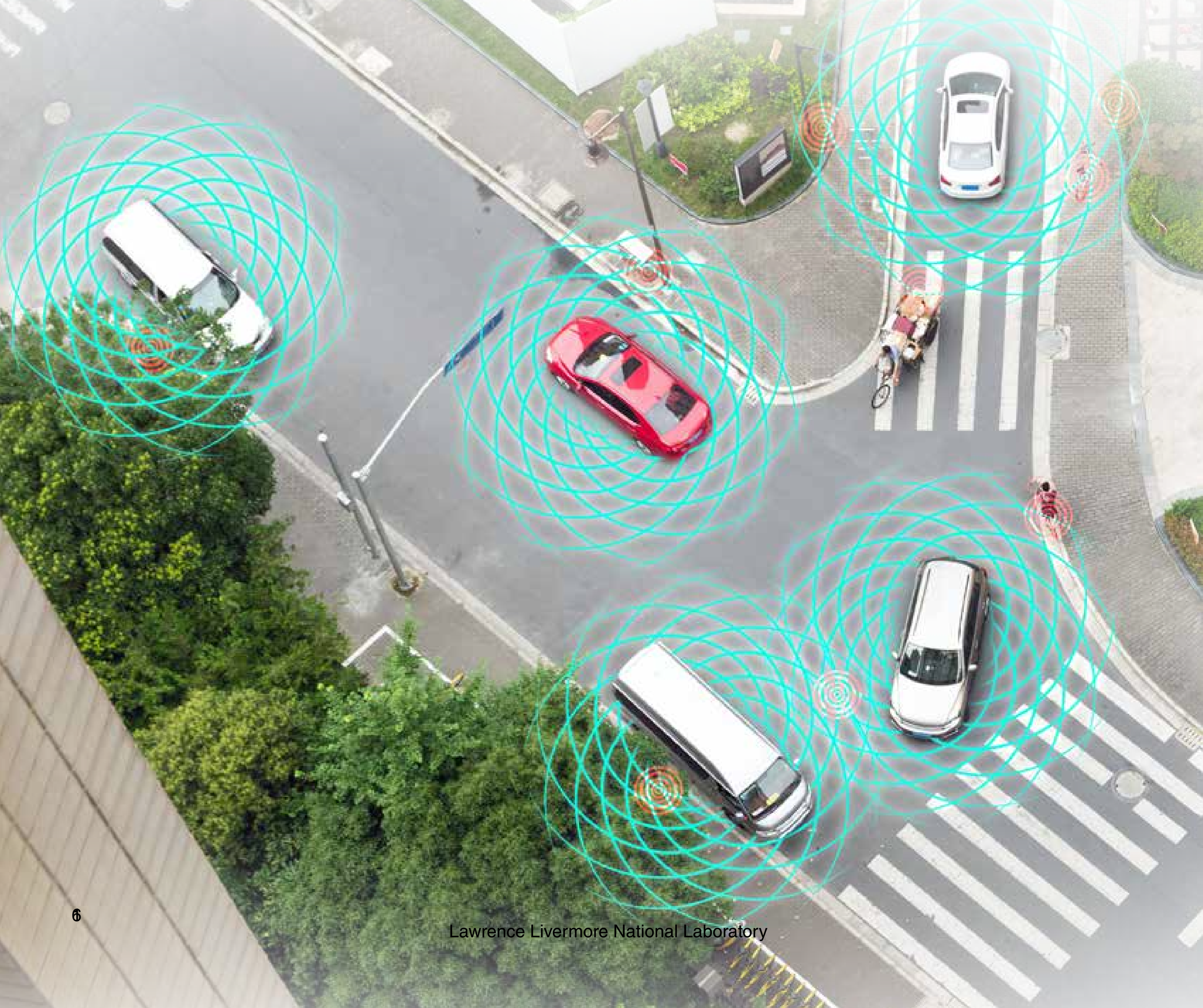


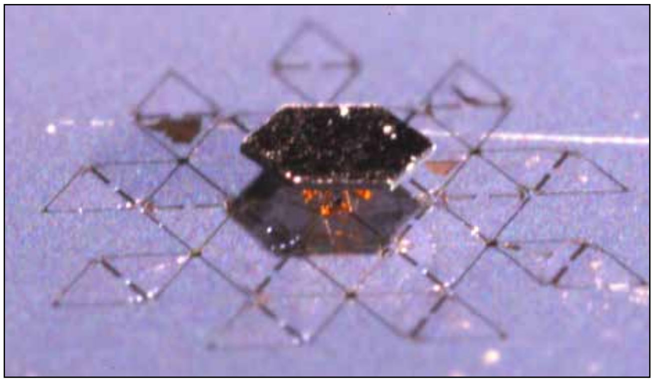
Borg is shown holding the sample wheel of a thermal ionization mass spectrometry system, which the cosmochemistry team uses to measure isotope ratios.

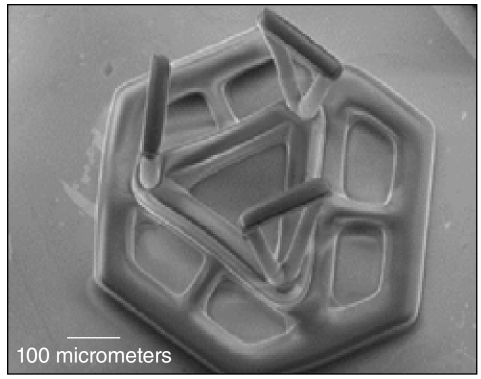
GUIDING LASER LIGHT

WITH THOUSANDS OF TINY MIRRORS

AN array of thousands of constantly moving hexagonal mirrors, each measuring just 1 millimeter square, could one day enable a host of cutting-edge applications, from self-driving cars and laser-based communication and manufacturing to advanced microscopes and telescopes. The Livermore micromirror array delivers an unprecedented combination of capabilities, including tight control of every mirror's three degrees of freedom—tip, tilt, and piston (up-and-down) motions. The result is significant improvement in the speed and precision with which the mirrors reflect and guide light.







Livermore's design for a micromirror array comprises upwards of 10,000 hexagonal-element arrays, each measuring 1 millimeter square. The images show (left) a single fabricated mirror and (right) three microflextures printed on the underside of a micromirror, awaiting attachment to a paddle.

Livermore engineer Bob Panas is principal investigator of the Light-field Directing Array Program, which developed the micromirrors. Panas explains, "This technology, which excels at controlling and directing light, is based on microscale structures for controlling arrays of miniature mirrors. This approach promises motion that is faster, greater in range, and more accurate than technologies currently on the market can deliver. New technologies like ours are needed to replace slow, expensive, and bulky conventional instruments."

Initially funded by the Laboratory Directed Research and Development Program, the micromirror array has sparked interest from U.S. firms seeking lidar (light detection and ranging) products for self-driving cars and from the Department of Defense, which is funding further development of the technology. Panas's team of seven engineers is producing an early prototype array of seven micromirrors for advanced testing and demonstration.

The development effort includes contributions from Jonathan Hopkins, assistant professor of mechanical and aerospace engineering at the University of California at Los Angeles and his colleagues, along with experts from A. M. Fitzgerald & Associates, a microelectromechanical system (MEMS) microfabrication consulting firm based in Burlingame, California. The array also takes advantage of resident Livermore expertise in advanced micromanufacturing capabilities, including additive manufacturing. The array, a MEMS application that consists of miniaturized mechanical and electromechanical components measured on the micrometer scale, is the culmination of a decade of research at Livermore exploring new applications for MEMS and better ways to fabricate the devices.

Dramatic Performance Gains

The Laboratory team's patented design offers dramatically enhanced performance compared to existing light-guiding technologies—approximately 100 times greater than other tip–tilt mirror array designs, as measured by the speed and range of the mirrors. Panas envisions upwards of 10,000 hexagonal-element arrays, each measuring 1 millimeter square and together covering a roughly 10-centimeter-square surface. Moving in unison, the tiny mirrors will operate like a single, large reflective device, with each mirror controlled independently to create the exact configuration needed. Fast and precise motion control achieves the exact tip, tilt, and pistonlike movements required. Each mirror can tip or tilt up to 10 degrees and move up or down as much as 30 micrometers in either direction. Moreover, each mirror can perform up to 40,000 fine angle adjustments per second. With this degree of control, light can be reflected in any desired direction. The array can even split the outgoing beams in different directions to map large areas in parallel, or quickly focus on any object of interest.

These performance enhancements give the mirror array potential applications in a wide range of fields, including optical switches, precision optical alignment, imaging, detection, communications, astronomy, three-dimensional (3D) displays, confocal microscopes, focusable lidar systems, beam combining, and high-powered laser steering systems. The devices could also make possible new approaches to micro-additive manufacturing.

The array is composed of identical miniaturized hexagonal units, each consisting of a mirror, three microscopic decoupling flexures, and three two-layer actuator paddles. These components are fabricated at Livermore with a combination of microfabrication, microassembly, and new micro-additive manufacturing techniques. The mirrors and paddles are fabricated in a manner similar to integrated circuits, whereas the microflexures are 3D printed.

To fabricate the mirrors, a silicon wafer is cut into hexagonal pieces and coated to reflect incoming light. The development team chose a hexagonal shape to achieve a 99 percent fill factor, that is, the ratio of mirror surface area to total device surface area. Panas explains, “We don’t want the device to absorb laser light. The higher the fill factor, the more light is reflected, reducing the possibility that a high-intensity incoming beam could damage the array.” Hexagons strike an ideal balance between dynamics and pattern fill, despite being relatively uncommon in other designs. A circle would be the optimal geometry for a tip–tilt mirror from the standpoint of balanced mass moments of inertia but would greatly reduce the fill factor.

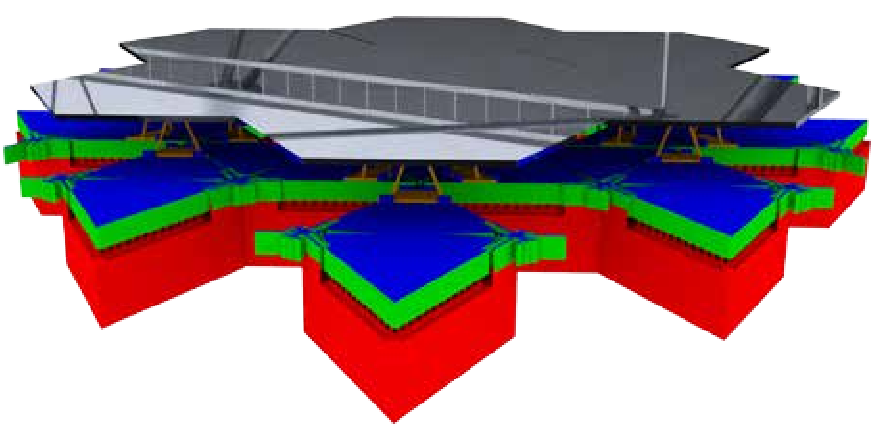
Microflexures Are Key

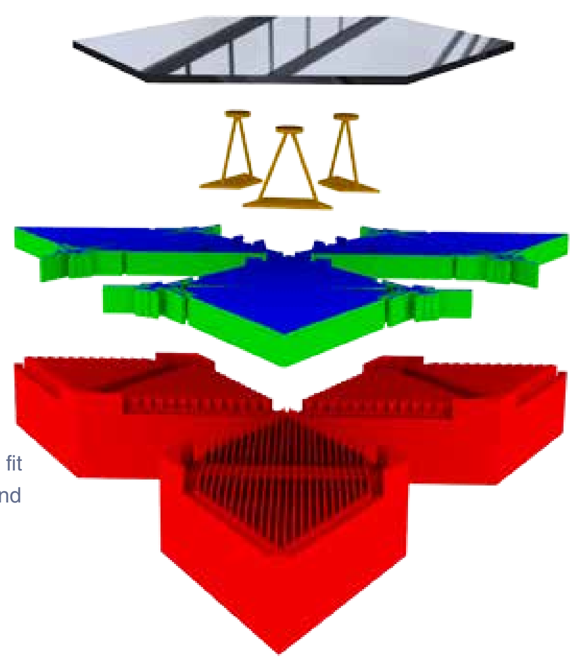
The microflexures—measuring just micrometers in diameter but playing an outsized role in the Livermore array design—are manufactured with techniques developed by Livermore’s micro-additive manufacturing group. Panas states, “Our microflexure design couldn’t be fabricated with any other method.” The three paddles that precisely move a mirror are connected to the mirror by a unique microflexure designed to operate at the extremely high loads experienced during rapid motions. Panas explains, “Nearly all other designs currently available are under-constrained, that is, free to vibrate at certain frequencies, which strongly limits their speed and accuracy. However, we get vastly improved performance with our design by utilizing exact-constraint principles.”

Each paddle is composed of two microfabricated silicon wafers. The actuator plate and the base plate (also known as the via plate) are aligned and then fused together. Electrically charged combs of the actuator plate mesh and overlap with combs of the base plate, and six holes punched in the base plate permit the passage of voltage and current. “This technology is one of the first micromirror arrays to demonstrate integrated closed-loop control,” declares Panas. “By measuring the capacitance in each paddle, we can determine where each mirror is without using an external sensor. If you know where the paddles are, you know where the mirrors are. This real-time feedback compensates for any unwanted motions. In contrast, open-loop mirror arrays inevitably suffer problems from manufacturing variations, temperature changes, and vibrations, which degrade precision.” With closed-loop control these problems are avoided by automatically adjusting the voltage delivered to any particular paddle, providing the ability to lock the device to the performance desired—even in a noisy, vibration-rich environment such as a moving vehicle. The array’s closed-loop control also provides a means to reject local disturbances and achieve the cleanest possible control for capturing clear telescopic images through atmospheric distortions.

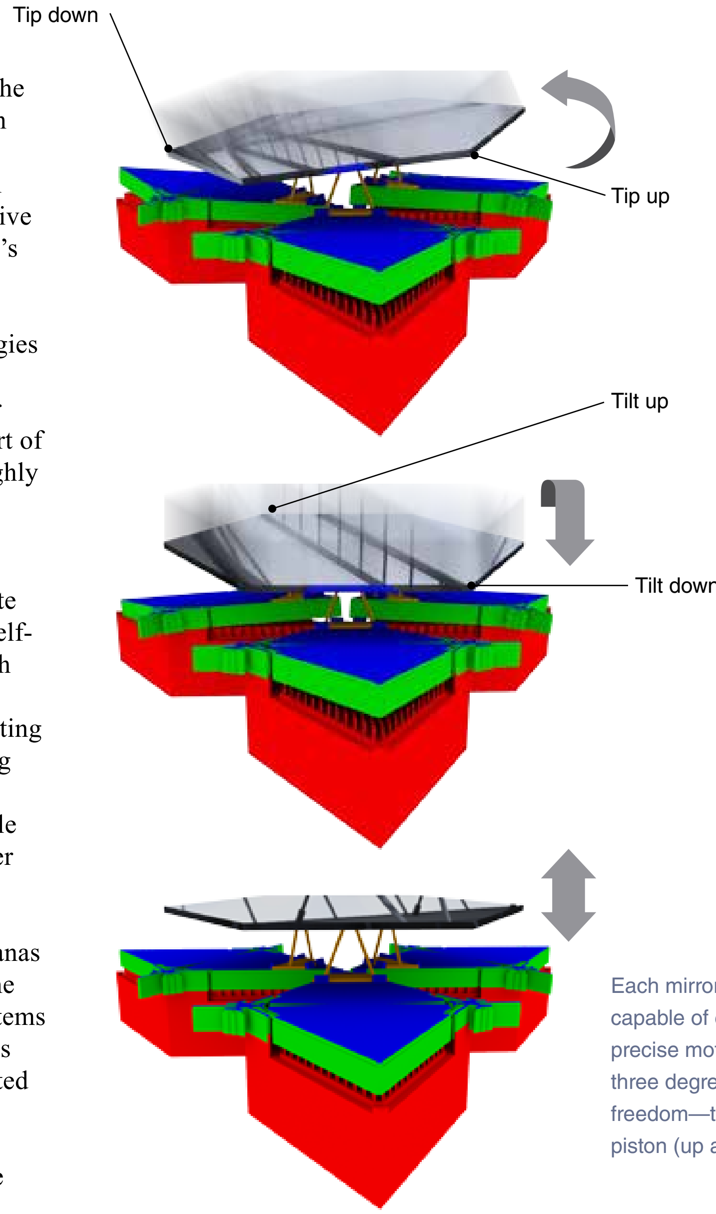
Applications Abound

The Livermore micromirrors make possible a host of new technologies and also promise to improve existing ones. Applications include secure laser communications on Earth and in space, including drone-to-drone communication for global Internet access. The large area of the array, combined with its high fill factor, make it possible to direct high-energy beams





Computer-aided design models show how the micromirrors are configured. (left) Seven mirrors fit together in a small array. (right) Sitting on the base plates (red), three actuator paddles (blue and green) precisely control the mirror (gray) by manipulating the flexures (gold).



Each mirror is capable of extremely precise motions in three degrees of freedom—tip, tilt, and piston (up and down).

without damaging the array, a capability that could improve the uniformity of light coming off the meter-scale mirrors used in laser systems such as the National Ignition Facility.

The microarray's attributes would be particularly useful in advancing the use of lasers in manufacturing, including additive manufacturing and micro- and nanomanufacturing. The array's precision and bandwidth could stabilize optics and adjust for misalignment to assure performance in noisy, high-thermal-variation environments, making exotic, new optical technologies a reality simply, quickly, and cheaply. Finally, because each tiny mirror can be individually adjusted, the aggregate mirror assembly could be precisely curved to make it function as part of an extremely high-resolution telescope that would also be highly resistant to vibration, drift, or thermal expansion issues.

The most immediate application for the micromirror array may be reducing the size and cost of bulky lidar units. Lidar uses a pulsed laser to measure distances remotely and generate high-resolution maps. High-speed, focusable lidar is key to self-driving vehicles, but existing systems struggle to achieve high refresh rates (greater than 20 hertz). Current lidar approaches also continuously scan a vehicle's entire surroundings, collecting massive amounts of data that may not be necessary to steering and other functions, and cannot focus on a specific object of interest. However, Livermore micromirror technology, capable of running up to 1,000 times faster and achieving much higher resolution, could locate and avoid objects sooner and farther away than conventional systems can, allowing a vehicle's autonomous controls to respond to road conditions sooner. Panas explains, "Instead of constant scanning where very little of the data are useful, the system can spend more time focused on items of interest and collect far more information of value." With its small size, the Livermore micromirror array could be integrated into a vehicle's taillights and other unobtrusive locations, for 360-degree coverage. Panas has been in discussions with lidar device manufacturers who are interested in licensing the Livermore technology.

Prospects are bright for using Livermore advances in additive manufacturing to create the micromirror array's minuscule parts. In fact, the micromirrors themselves could one day enable a new additive manufacturing paradigm, guiding "optical tweezer" laser beams to sinter millions of nanoparticles simultaneously. Such a feat would be a fundamental advance in a crucial manufacturing field.

Panas predicts his team will expand to meet rapidly growing interest in the Livermore technology and its many potential applications. Thousands of precise micromirrors acting in unison may one day be central to everything from self-driving cars to new manufacturing technologies.

—Arnie Heller

Key Words: additive manufacturing, Laboratory Directed Research and Development Program, lidar, light-field directing array, microelectromechanical system (MEMS), micromirror, micro-additive manufacturing.

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LABORATORY OUTREACH PROGRAMS INSPIRE THE NEXT GENERATION

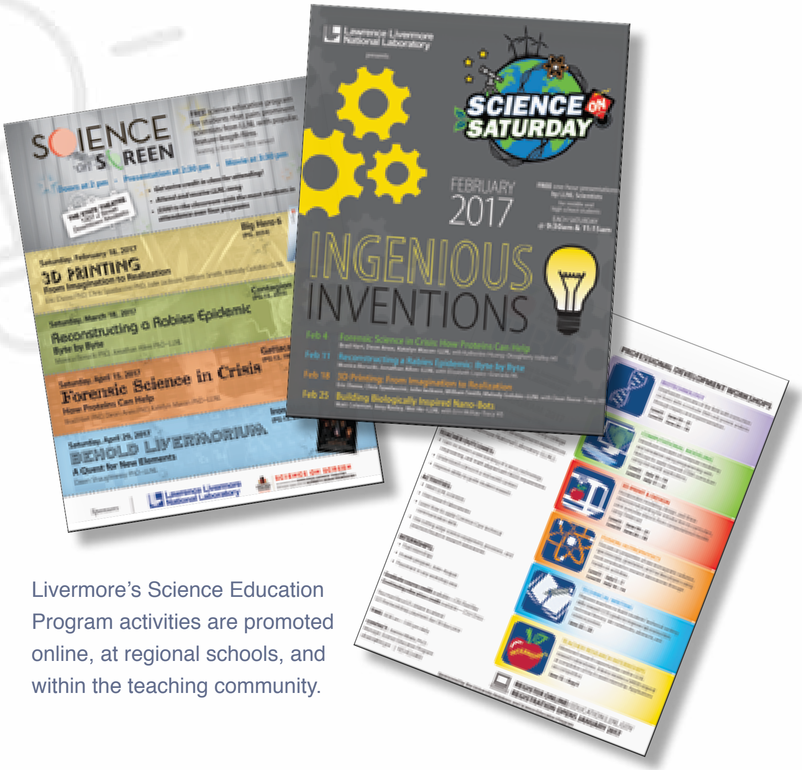
UNDERLYING Lawrence Livermore's national and global security missions is the need for a continually engaged, trained, and inspired workforce. The quality and accessibility of science, technology, engineering, and math (STEM) education help shape future generations of scientists and engineers. To this end, the Laboratory's Director's Office oversees a multipronged outreach effort administered by the Science Education Program—part of the University Relations and Science Education Office—and by the Public Affairs Office.

As the Laboratory celebrates its 65th year in Livermore, California, promoting STEM literacy is also a way to give back to the region. This outreach relies on deep engagement with school districts in surrounding communities. Joanna Albala, Science Education Program manager, describes the Laboratory as a

Livermore's Fun with Science booth engages children of all ages at the Bay Area Science Festival Discovery Day. (Photograph by Don Johnston.)

community steward. "Our programs show the public what kind of work Lawrence Livermore is doing in their backyard," she says.

Educational outreach is vital to all Laboratory organizations, as evidenced by a range of student internships and academic partnerships. At the institutional level, the Laboratory approaches STEM education as occupying a continuum, from elementary school to early career. Public Affairs Director Lynda Seaver says, "The Laboratory prides itself on hiring the best and the brightest, so it's incumbent on us to bolster STEM foundations." Lawrence Livermore has invested in facilities and curricula that help accomplish that goal. The Discovery Center provides interactive displays and demonstrations, and workshops and career panels are held at the Edward Teller Education Center. Among the most popular programs are Fun with Science, Science on Saturday, and the Teacher Research Academy (TRA) program.



Livermore's Science Education Program activities are promoted online, at regional schools, and within the teaching community.

Field Trips and Road Shows

Each year, more than 8,000 students visit the Laboratory to experience the Fun with Science program. Tailored to fourth and fifth graders, the program begins with a tour of the Discovery Center, followed by staff-led, hands-on demonstrations and experiments that explore electricity, density, states of matter, and other basic scientific concepts. In one popular demonstration, a Laboratory scientist—a retiree or employee volunteer—makes "elephant's toothpaste" in a clear graduated cylinder. The presenter mixes hydrogen peroxide with a few drops of dish soap and food coloring, then adds potassium iodide as a catalyst. Livermore scientist and Fun with Science volunteer Laura Berzak Hopkins explains, "What starts as a small amount of soapy liquid ends up as frothy, bubbly 'toothpaste' overflowing out of the cylinder. The class always reacts with surprise and laughter. This demonstration is a great opportunity to introduce terminology without it becoming a dry dictionary discussion."

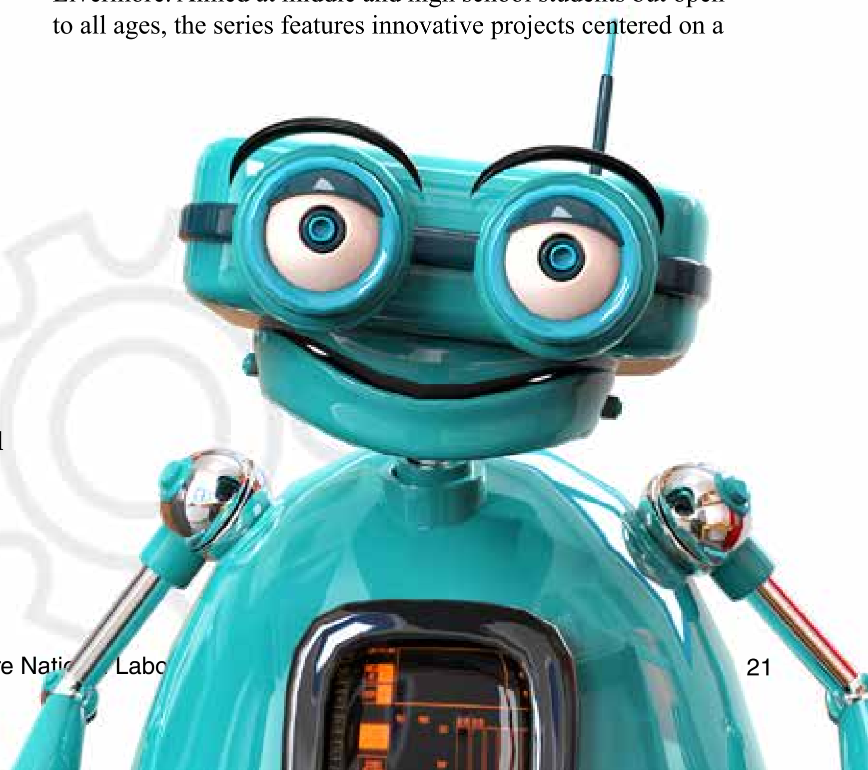
The Fun with Science team contributes to the Bay Area Science Festival Discovery Day, held once a year at AT&T Park in San Francisco. Laboratory volunteers run a booth stocked with hands-on experiments, games, and trivia questions. The event is geared toward families with children up to age 14, and attendance in recent years has topped 30,000. Seaver observes, "It's also great to see how interested the parents are. They learn something, too."

After two decades, the Fun with Science repertoire now includes local involvement with the Exceptional Needs Network's summer camps for developmentally disabled children and Family Science Night hosted by California state legislators. In its third year, STEM Day at the Laboratory encourages underrepresented and underserved middle and high school students toward STEM pursuits. Last year, the program hosted over 400 middle school students for a fun day of STEM education. Seaver states, "Our goal is to reach every student in the Livermore school district at some point during the elementary, middle, or high school years."

The program sees steady participation year-round, and volunteers like Berzak Hopkins enjoy preparing attendees for school science classes. She says, "Rather than thinking of science as a school subject that's hard or boring, students can start to build a new association, one that sees science as fun, interesting, and something they can take part in." Seaver confirms, "Our volunteers have a zeal for translating science for young minds. Kids feed off that enthusiasm."

Weekend Wisdom

Every weekend in February, the Laboratory holds weekly Science on Saturday lectures at the Bankhead Theater in downtown Livermore. Aimed at middle and high school students but open to all ages, the series features innovative projects centered on a



theme. Laboratory scientists lead each talk, assisted by local high school teachers and students. Albala states, "For the Livermore area, Science on Saturday has become a local staple, like the farmers' market."

National Ignition Facility (NIF) physicist Tammy Ma first attended Science on Saturday in eleventh grade. She says, "Over multiple seminars, I learned about lasers, spectroscopy, and meteors. I recall attending a lecture on NIF and thinking how cool it was." When Ma delivered her own Science on Saturday talk 16 years later, she quickly appreciated the challenge of communicating NIF's mission to a general audience. "Conveying the enormous progress we've made toward fusion ignition is incredibly complex. By going through the exercise of preparing a Science on Saturday talk, I now have a much better sense of how to talk about our work in an understandable way."

The series has grown in popularity since its inception in 1999, and efforts are ramping up to bring the series to cities in the broader community. To reach an even larger audience, videos of events are published on Lawrence Livermore's YouTube channel and broadcast on the University of California's television station. A spinoff series, Science on Screen, pairs a staff scientist with a feature-length movie at the State Theatre in Modesto, California. At both Saturday events, students can ask questions about the science described in the lecture or shown in the movie. Ma speaks from experience when she states, "Science on Saturday helped me to see the different types of science out there, and to get a better feel for what application-driven innovation really means. It played a big role in my choosing to study science in college."

In an experiment that illustrates basic chemistry concepts, hydrogen peroxide reacts with dish soap and potassium iodide to create "elephant's toothpaste."

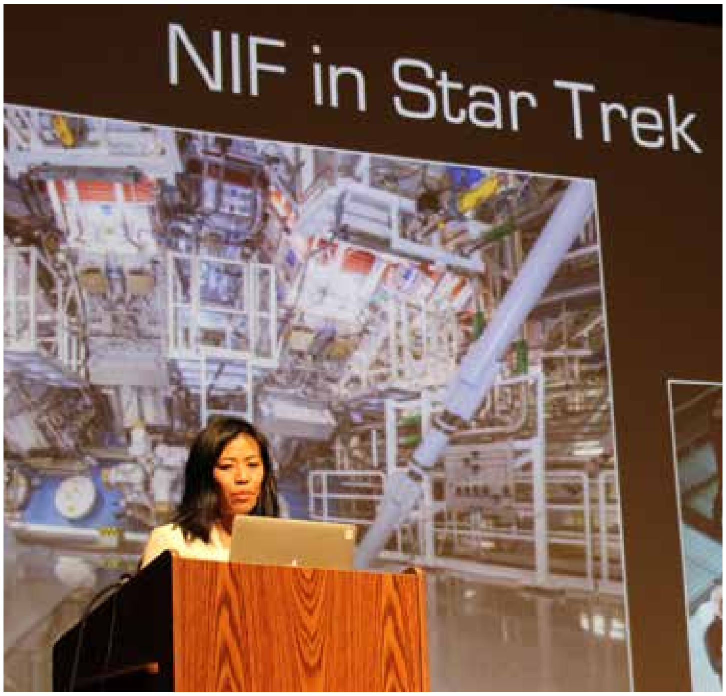
Professional Development

Since the mid-1990s, the Laboratory has offered summer workshops to middle and high school teachers through the TRA program. The current curriculum includes four levels of instruction across six disciplines—biotechnology, climate change, computer modeling, fusion and astrophysics, technical writing, and three-dimensional (3D) printing—and aligns with California and national science standards. Teachers pursuing a master's degree at California State University, East Bay, can earn graduate-level credits through the TRA program.

In Level I, teachers build introductory skills and knowledge in their chosen discipline. In Level II, participants receive more days of instruction with a deeper topical dive. Level III includes job shadowing and preparation for the eight-week mentored internship of Level IV, in which teachers can contribute to real-world problems and publish their work. Albala says, "If you reach one teacher, you can reach thirty to a hundred of that teacher's students."

The TRA program is designed to accommodate participants' teaching schedules, and the courses are taught in the summer by "master teachers" who have been through the program themselves. This unique format allows teachers from multiple school districts to learn from master teachers and Laboratory scientists, work with fellow educators, and bring new knowledge back to their classrooms.

Erin McKay began attending the TRA program in 2003, and since completing all four biotechnology levels, she has spent her summers as a master teacher. At Tracy High School, McKay is responsible for teaching biotechnology—molecular genetics and



During a Science on Saturday lecture, Livermore scientist Tammy Ma describes the concept of fusion and the National Ignition Facility's role in national energy security. (Photograph by Joanna Albala.)

During STEM Day at the Laboratory, interactive exhibits include a plasma globe (shown above), a bicycle that generates electricity, and three-dimensionally printed objects. (Photograph by George Kitrinos.)

bioinformatics on top of a baseline biology curriculum—to 11th and 12th graders. She explains, "I participate in the TRA program to make sure I have the resources to teach my advanced courses. I don't want to be stagnant."

A Full Calendar

Lawrence Livermore responds to consistently high demand for STEM education opportunities both on- and offsite, hosting tours and sponsoring STEM events around the San Francisco Bay Area and San Joaquin Valley. For example, Livermore sponsors the San Joaquin and Tri-Valley Expanding Your Horizons conferences, which offer STEM workshops and career fairs. Albala describes the Laboratory's roster of activities as increasing STEM learning at critical moments. She states, "The Science Education Program provides tours to high schoolers and pre-service teachers who are at a critical point in their science education." Other events include the onsite Community College 3D Design Summer Academy (a one-week workshop) and offsite lectures at Las Positas Community College in Livermore.

To continue the cycle of outreach, the Science Education Program and Public Affairs Office encourage as many Laboratory scientists and engineers as possible to volunteer in educational programs. Annie Kersting, director of the Laboratory's University Relations and Science Education Office, says, "I am thankful our staff help ensure our STEM outreach programs continue to excite and engage the next generation. One day, we hope these children become our future workforce." For Ma, being a scientist carries a responsibility for outreach. She states, "It's important to continuously remind the public of the essential role science and technology play in driving innovation and economic growth, and to engender that trust so that when policy decisions are being made, the scientific rationale is taken seriously."

—*Holly Auten*

Key Words: community outreach; Discovery Center; Edward Teller Education Center; Fun with Science; Science Education Program; Science on Saturday; science, technology, engineering, and math (STEM) education; Teacher Research Academy (TRA).

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In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven-digit number in the search box at the U.S. Patent and Trademark Office's website (http://www.uspto.gov).

Patents

Enhanced Multifunctional Paint for Detection of Radiation
Joseph C. Farmer, Edward Ira Moses, Alexander M. Rubenchik
U.S. Patent 9,588,229 B2
March 7, 2017

Cementing a Wellbore Using Cementing Material Encapsulated in a Shell
Roger D. Aines, William L. Bourcier, Eric B. Duoss, William C. Floyd, III, Christopher M. Spadaccini, John J. Vericella, Kenneth Michael Cowan
U.S. Patent 9,593,552 B2
March 14, 2017

Shape Memory Polymer Foams for Endovascular Therapies
Thomas S. Wilson, Duncan J. Maitland
U.S. Patent 9,597,085 B2
March 21, 2017

High-density 3D Graphene-Based Monolith and Related Materials, Methods, and Devices
Marcus A. Worsley, Theodore F. Baumann, Juergen Biener, Supakit Charnvanichborikarn, Sergei Kucheyev, Elizabeth Montalvo, Swanee Shin, Elijah Tylski
U.S. Patent 9,601,226 B2
March 21, 2017

High-Performance Rechargeable Batteries with Nanoparticle Active Materials, Photochemically Regenerable Active Materials, and Fast Solid-State Ion Conductors
Joseph C. Farmer
U.S. Patent 9,614,251 B2
April 4, 2017

Awards

Lawrence Livermore received an **"A" grade** on last fall's **Organization for the Prohibition of Chemical Weapons** (OPCW) proficiency test, marking the seventh straight "A" grade garnered by Laboratory researchers. Each October, laboratories from around the world take part in OPCW tests, attempting to identify simulated chemical weapons compounds in samples. To retain OPCW certification, Livermore and the other OPCW-designated laboratories must maintain a three-year rolling average of at least two "A" grades and one "B" in ongoing proficiency tests, which are designed to be some of the most difficult analytical challenges that scientists can face.

The Laboratory's OPCW efforts, performed at the Forensic Science Center, are led by **Armando Alcaraz**. Researchers who also participated the OPCW testing included **Cynthia Alviso, Deon Anex, Sarah Chinn, Todd Corzett, Mark Dreyer, Brad Hart, Saphon Hok, Carolyn Koester, Roald Leif, Katelyn Mason, Brian Mayer, Daniel Mew, Tuijuana Mitchell-Hall, Michael Riley, Edmund Salazar, Robert Schmidt, Carlos Valdez, Alexander Vu,** and **Audrey Williams**.

Each OPCW test is different, and the spiking materials and matrices can vary in complexity. A research laboratory that misidentifies a compound or reports a false positive could receive an "F" and lose its OPCW laboratory designation. Out of the 21 laboratories that participated in the latest test, 14 received "A" grades, 2 received "Bs," 1 received a "C," 3 received "Ds," and 1 received an "F."

David Weisz, a chemist in the Chemical and Isotopic Signatures Group, was awarded the inaugural **Dr. Ian Hutcheon Postdoctoral Fellowship** by the **National Technical Nuclear Forensics Center** of the Department of Homeland Security's Domestic Nuclear Detection Office. The award is open to postdoctoral researchers at all national laboratories, and its purpose is to attract future leaders to the field of nuclear forensics.

The prestigious fellowship is named in honor of the late Ian Hutcheon, who was a longtime nuclear forensics expert and former leader of Lawrence Livermore's Chemical and Isotopic Signatures Group. Hutcheon had mentored Weisz for two years as the latter worked toward his doctorate. Under the fellowship, Weisz will collaborate with a multidisciplinary team of Livermore scientists and conduct research on the fundamental physics and chemistry of fallout formation with applications to postdetonation nuclear forensics.

The **East Bay Economic Development Alliance**—a regional network of business leaders, educators, and elected officials who work to strengthen the East Bay's economy—recognized the outstanding success of the Laboratory's **Engineering Technology Program for Veterans** ("Vets to Tech") by honoring it with its **Education Award**. A collaboration between Livermore, Las Positas College, the Alameda County Workforce Investment Board, and the training nonprofit Growth Sector, Vets to Tech gives veterans on-the-job experience as they continue their education in engineering, math, and physics.

A broader goal of the program is to help tech-savvy veterans returning from military service transition to civilian life. Established in 2014, the homegrown approach is also a Laboratory workforce pipeline for veteran students that gives them skills training, paid internships, and a gateway to future employment at Livermore. Through the program, veterans at Las Positas College can earn a two-year degree in mechanical engineering as they get real-world experience during a 10-week internship at the Laboratory, which is often extended into part-time and later full-time work. Livermore has already hired six of the program's first eight graduates.

Abstract

The Widest, Deepest Images of a Dynamic Universe

The Large Synoptic Survey Telescope (LSST) promises to unlock mysteries of the universe in astronomical proportions. During its 10-year survey of the skies, this cutting-edge telescope is expected to make myriad unexpected discoveries and catalog billions of objects, from icy comets to stealthy planetoids, exploding stars, newborn galaxies, and everything in between. For this multinational collaborative effort, Lawrence Livermore has made groundbreaking contributions to how LSST is built and operated. From a mountaintop in Chile, LSST's wide, deep, and fast survey will each night conduct 1,000 visits covering a third of the sky above the Southern Hemisphere. This cadence will generate 5.5 million photos and create "the first motion picture of our universe," but LSST will have to move like a racecar among telescopes to accomplish its science goals. LSST core science areas are (1) investigating the nature of dark matter and dark energy, (2) cataloging hazardous asteroids and the remote solar system, (3) exploring the changing sky, and (4) understanding the formation and structure of the Milky Way. Seeing objects 9 million times fainter than what is detectable by the unaided human eye, LSST's 3.2-gigapixel camera will use the largest high-performance lens ever built to capture a staggering 60 petabytes of data over the course of its mission.

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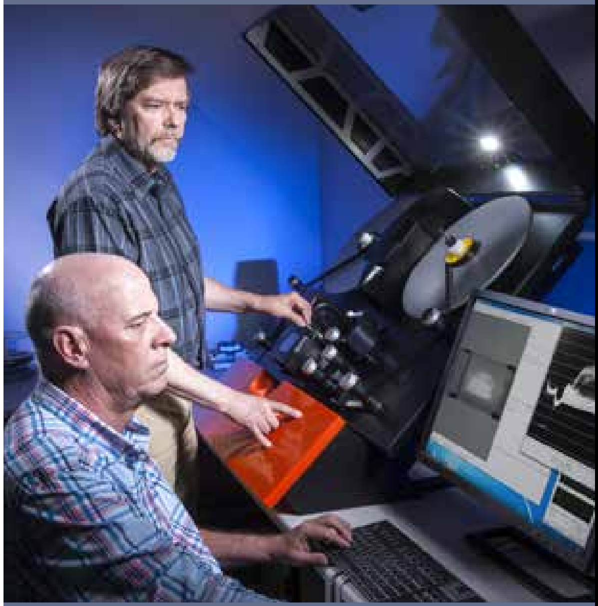
Valuable Data in Restored Test Films



Advanced technology revives Cold War–era film reels, providing important new data for modern nuclear weapons science.

Also in October/November

• Livermore researchers use additive manufacturing techniques for the tooling-free fabrication of specialized foams.

• Enhanced safeguards result from a 25-year effort to certify a plutonium reference material.

• By shocking matter into changing phase at ultrahigh pressure, scientists are revealing new physics.

Coming Next Issue

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