Program Overview

Laboratory Directed Research and Development

Lawrence Livermore National Laboratory

Fiscal Year 2021

Annual Report

Lawrence Livermore National Laboratory

LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

Annual Program Overview

Over the last three decades, the Laboratory Directed Research and Development (LDRD) Program has funded Lawrence Livermore National Laboratory (LLNL) research to address today's national security challenges and future mission needs. In this annual report, we summarize how LLNL uses targeted investments to develop cutting-edge capabilities, advance our knowledge in strategic science and technology domains, develop our world-class workforce, and foster innovation in key programmatic areas.

August 2021 marked a milestone event in our laboratory's history: arriving at the threshold of fusion ignition at NIF. This report describes how LDRD investments played important roles in advancing our capabilities and scientific understanding to deliver this outstanding result of a 1.3 megajoule yield. We also highlight the partnerships across the DOE and NNSA complex that were instrumental to our success. LDRD investigators are key to the technical vitality of LLNL, pushing the frontiers of science and technology, using our capabilities in high-energy-density science, materials science, engineering, and high-performance computing. Within inertial confinement fusion their research accelerates solutions in multiple areas, including new diagnostic capabilities, novel target design and fabrication techniques, and laser and optical science. This remarkable achievement is central to our stockpile stewardship mission and opens new avenues for research on the most extreme states of matter in the universe.

> "The LDRD program brings together diverse teams and collaborators to innovate mission-driven solutions, advance the frontiers of science and technology, and develop our world-class workforce."

In addition, LDRD investments foster mission agility through multidisciplinary research, bringing together diverse teams and collaborators to innovate solutions to fulfill our missions. For example, investigators are exploring new ways to address challenges in nuclear weapons science, nuclear threat reduction, space security, cybersecurity, and energy security. As you browse this report, you will learn about projects that utilize LLNL's core competencies in areas such as advanced manufacturing, optics, high-performance computing, and simulation.

Kimberly S. Budil
LLNL Director

Finally, our LDRD program cultivates the creativity of the Lab's most important resource—our workforce. LDRD-sponsored research enables outreach to tomorrow's innovators, as we mentor students, hire postdoctoral researchers, and develop the leadership capabilities of early career staff. The mentorship aspect is a hallmark of our program. A multidisciplinary group of senior scientists and advisors encourage our staff to pursue new research directions.

Throughout this year's report, we highlight LDRD's investments in ideas that make the world a safer place. We review key accomplishments and performance indicators, and share highlights from projects led by our talented staff. I encourage you to visit our LDRD website and learn more about the 263 projects that we supported during fiscal year 2021. Looking to the future, I am confident that LDRD investments will continue to help LLNL remain at the forefront of innovative research and development.

ldrd-annual.llnl.gov

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Lawrence Livermore National Laboratory

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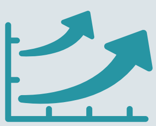
Program Description

The LDRD program's targeted investments allow LLNL to develop cutting-edge capabilities and foster innovation in key programmatic areas.

Technical Vitality



Mission Agility

Workforce Development

Mission Alignment

Congress established the Laboratory Directed Research and Development program in 1991 to foster cutting-edge scientific and technical vitality at U.S. Department of Energy (DOE) laboratories. The LDRD programs at each laboratory are a unique resource, providing funding for critical research aimed at addressing today's needs and tomorrow's challenges. LLNL's program addresses DOE objectives, while also aligning with National Nuclear Security Administration (NNSA) mission objectives and the Laboratory's own strategic priorities.

As articulated in DOE Order 413.2C, the LDRD program serves to:

- Maintain the scientific and technical vitality of the laboratories.
- Enhance the laboratories' ability to address current and future DOE/NNSA missions.
- Foster creativity and stimulate exploration of forefront areas of science and technology.
- Serve as a proving ground for new concepts in research and development.
- Support high-risk, potentially high-value research and development.

Alignment with NNSA Mission Objectives

A strategic framework—created jointly by NNSA, LLNL, and the other NNSA laboratories—articulates the focus of LDRD programs at NNSA laboratories. LDRD investments support the following NNSA objectives:

- Technical Vitality. Develop innovative capabilities that are required to respond to emerging national security challenges.
- Mission Agility. Enable agile responses to national security challenges by investing in research and development at the forefront of mission-critical science and technology.
- Workforce Development. Recruit, develop, and retain the best and brightest staff, who can help us creatively address tomorrow's dynamic mission needs.

Alignment with Laboratory Missions

In addition to aligning our LDRD investments with DOE and NNSA objectives, we ensure that our LDRD program supports mission priorities articulated in LLNL's annual strategic investment plan. Institutional goals are established and updated through a planning process where multidisciplinary teams identify:

- Mission-related challenges or areas of interest for high-priority research.
- The core competencies that support this high-priority research.
- The scientific and technological needs to address those challenges and enhance related competencies.
- Key topics in fundamental research.

Program Oversight

Day-to-day oversight of our program is provided by LDRD Program Director Doug Rotman. Overall program oversight extends beyond the LDRD program office to include the LLNL director and the LLNL deputy director for science and technology, along with the Laboratory's programmatic leaders. This local team works closely with NNSA's Livermore field office, NNSA's LDRD program leaders, and LDRD program leaders at the Department of Energy.

At the programmatic level, LDRD portfolio management at Livermore is structured to assure alignment with DOE, NNSA, and Laboratory missions. Designated LDRD points of contact for each of the Laboratory's strategic investment areas provide input regarding LDRD investment priorities to Livermore's senior leadership team. These points of contact also advise applicants for LDRD funding regarding the alignment between proposed research and evolving mission needs at our Laboratory.

In addition, programmatic leaders and science and technology leaders participate in a rigorous peer-review process of all proposals for LDRD funding. They evaluate the strategic relevance of each proposal, as well as its technical content. NNSA reviews and concurs on funding decisions. Funded projects are periodically reviewed by senior staff to ensure technical success and continued alignment with mission objectives.

Performance Indicators Drive Program Improvement

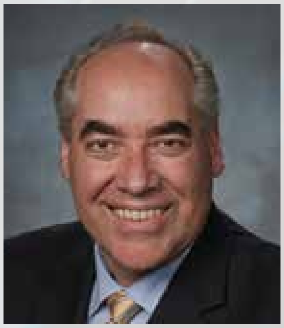
The LDRD program achieves continuous improvement through internal and external reviews of the program, along with oversight of each LDRD research project. Representatives from LDRD programs at each NNSA laboratory regularly participate in working groups to share best practices and discuss strategies for tracking the long-term impact of LDRD investments.

In FY20, the NNSA working group finalized a combination of common quantitative and qualitative long-term indicators, emphasizing a systematic approach to tracking and reporting performance indicators. For fiscal year 2021, we presented a common set of long-term performance indicators, which can be found in the Program Value section of this report. Our report also includes performance indicators specified by DOE's director of LDRD programs, in accordance with DOE Order 413.2C.

PATRICIA FALCONE

LLNL Deputy Director for Science & Technology

"The LDRD program is an essential component of our mission-driven strategy and is closely aligned with the Investment Strategy for Science and Technology. At the LDRD proposal stage, principal investigators articulate how their proposed research advances our investment priorities. The innovative projects help our LLNL community sustain world-class science and technology and contribute to broader scientific research."



DOUG ROTMAN

LDRD Program Director

"The LDRD program is an investment in our nation's future, with a mission impact that is often realized many years after an LDRD-sponsored project concludes. I'm extremely proud of everyone at LLNL—from postdocs who serve on LDRD-funded research teams, to senior scientists who help shape our investment strategy—so that together, we can ensure that the LDRD program continues to serve as a valuable national asset."

Investment Portfolio

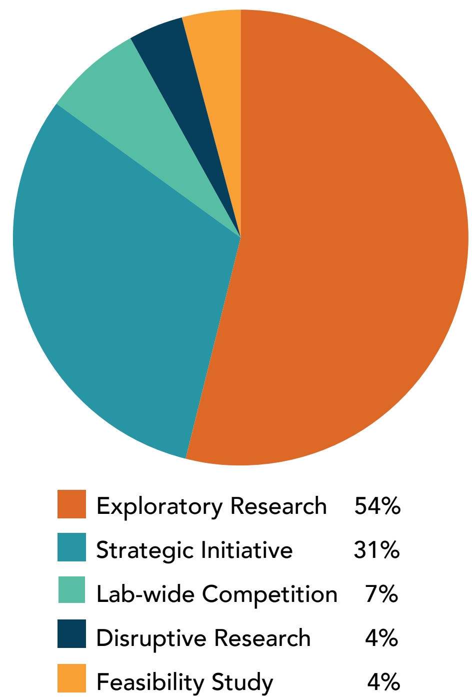
LDRD investments span a broad range of research topics, helping to ensure that LLNL supports innovation in key programmatic areas. Funded projects address some of our newest mission spaces, including cognitive simulation, predictive biology, space science and security, and hypersonic science. We also invest in the core capabilities and programmatic areas that undergird our Laboratory's technical vitality and mission agility.

For fiscal year 2021, we carefully structured Livermore's LDRD investment portfolio to promote the short-term objectives and long-term goals of DOE, NNSA, and our Laboratory. The key metrics presented here regarding our FY21 investment portfolio reflect this structure, including how funds are distributed across the program's 5 types of projects and 17 research categories. By strategically selecting the types of projects we fund, along with the amount of funding invested in each project, we help ensure a strong program portfolio.

FY21 INVESTMENTS
263 PROJECTS
$132M TOTAL FUNDING

Funding by Project Type

Livermore's LDRD program includes five types of projects. Each one has a distinctive purpose, duration, and funding limits. For example, our one-year feasibility studies support relatively brief investigations of a specific technical approach. These types of projects can be launched mid-year to rapidly respond to an emerging challenge. Other types of projects span several years, often involving collaborators and research that tackles a broader scope of challenges.



Project Type	FY21 Projects Funded	Project Aim
Exploratory Research	144	Address a specific research challenge or enhance a core competency.
Feasibility Study	51	Determine the viability of a new way to address a mission-relevant challenge.
Lab-wide Competition	41	Conduct innovative basic research and enable out-of-the-box thinking.
Strategic Initiative	18	Make significant progress addressing a mission-relevant challenge from a multidisciplinary perspective.
Disruptive Research	9	Pursue novel ideas with the potential to overturn fundamental paradigms or create new research directions.

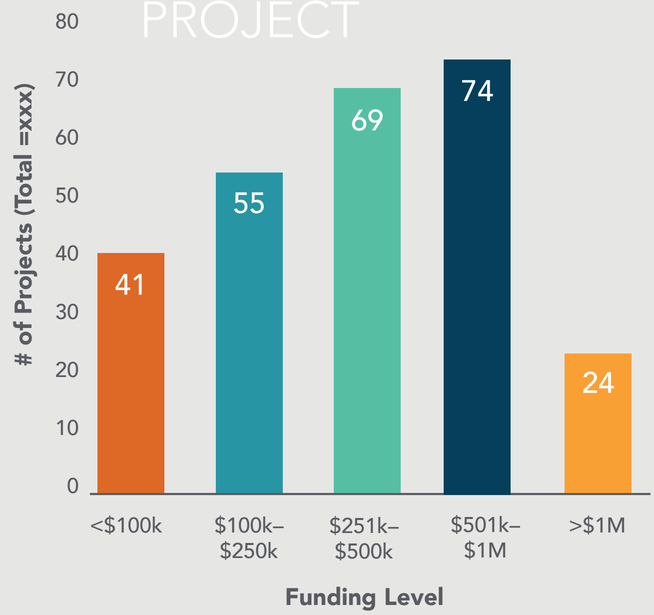
Projects by Funding Level

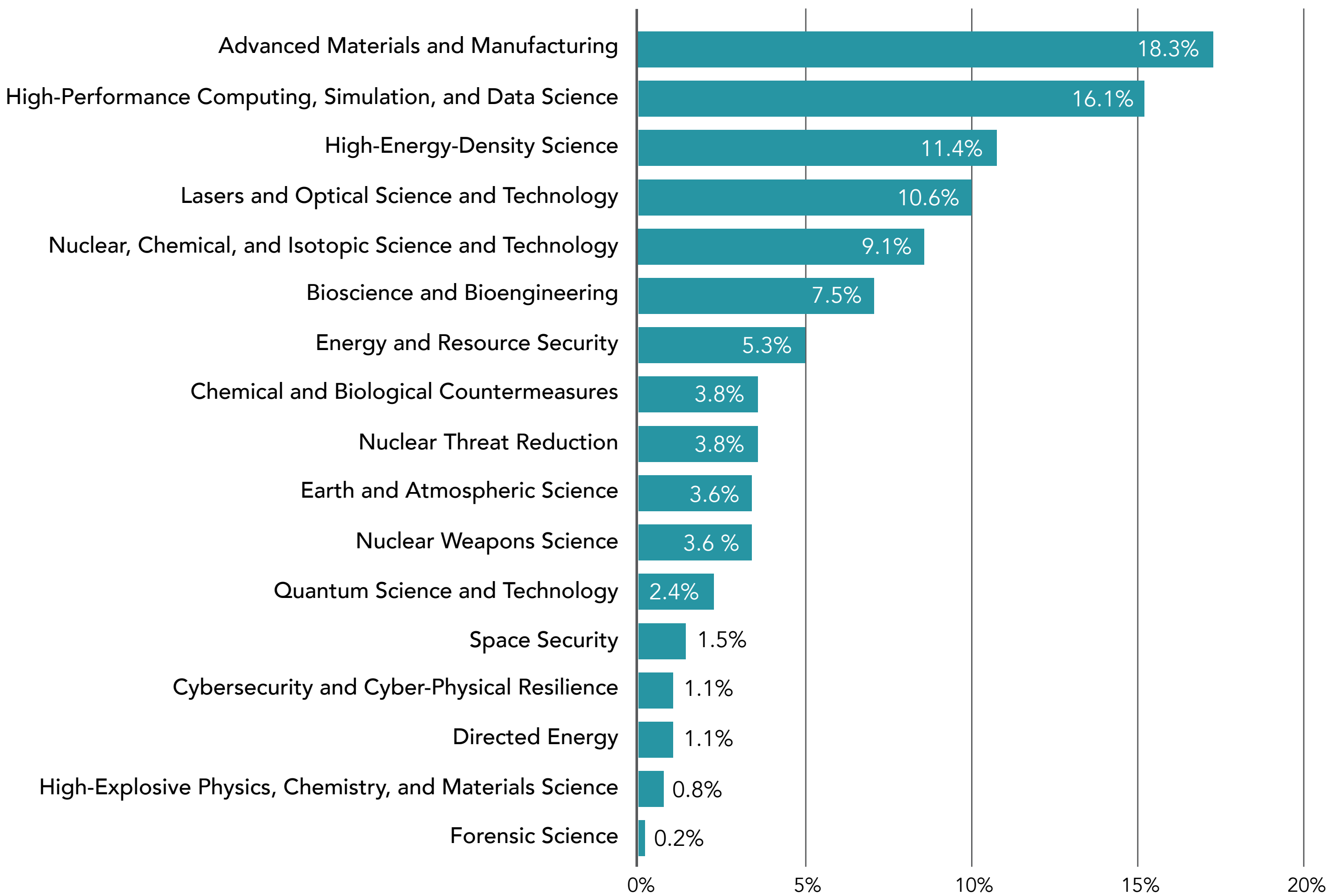
Our Laboratory's investment strategy includes the flexibility to fund projects at varying dollar amounts, depending on the project scope. This chart presents data on the number of projects funded in FY21, distributed across five funding levels. The largest number of projects (74) fell in a higher funding range, receiving between $501k and $1M per project. A smaller number of projects received less than $100k in funding (41 projects), or more than $1M in funding (24 projects).

Funding by Research Area

Every LDRD project is assigned to at least one of the Laboratory's research areas in the LDRD investment portfolio. The categories include 10 mission-driven research challenges and 7 core competencies—capabilities that enable us to conduct high-priority, mission-relevant research. (Note that this chart only includes research categories where at least one project designated the category as a primary research focus.)

$504,000 AVERAGE FUNDING LEVEL PER PROJECT





Program Value

By almost any measurement, the LDRD program contributes far more in publications, intellectual property, collaborations, and recruitment of postdoctoral researchers—dollar for dollar—than any other program at the Laboratory.

62 INSTITUTIONS
partnered with LLNL as part of LDRD-funded research teams in FY21.

Collaborative Explorations

External collaborations are essential to the innovative research that takes place at LLNL, including LDRD-funded projects. By collaborating with other national laboratories, academia, and industry, our investigators can engage with experts from these institutions and access to their world-class experimental facilities.

The following table provides our most recent data regarding formal collaborations, which we define as LDRD-funded projects where an external collaborator received LDRD funds from LLNL. In addition, our investigators frequently participate in informal collaborations with researchers at other institutions, which often involves joint scientific publications. Both types of collaborations are a key indicator of the broad intellectual engagement that is a hallmark of LLNL's research environment.

Collaborations	FY17	FY18	FY19	FY20	FY21
LDRD-funded projects with one or more formal collaborations	62	74	74	78	88
Percentage of all projects at LLNL	29%	31%	30%	32%	33%

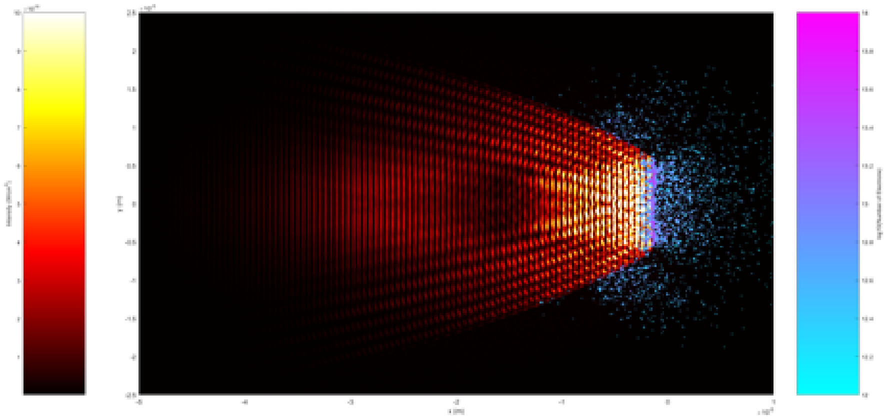
Scientists focus on cone targets to enhance temperature of electron beams

Intense short-pulse laser-driven production of bright high-energy sources, such as x rays, neutrons, and protons, has been shown to be an invaluable tool in the study of high-energy-density science.

To address some of the most challenging applications, such as x-ray radiography of high areal density objects for industrial and national security applications, both the yield and energy of the sources must be increased beyond what has currently been achieved by state-of-the-art high-intensity laser systems.

An LDRD-funded research team at LLNL partnered with the University of Texas at Austin and General Atomics to take on this challenge. Specifically, the team conducted experimental measurements of hot electron production using a short-pulse, high-contrast laser on cone and planar targets.

The cone geometry is a Compound Parabolic Concentrator (CPC) designed to focus the laser to the tip. The cone geometry shows higher hot electron temperatures than planar foils. Simulations identified that the primary source of this temperature enhancement is the intensity increase caused by the CPC.



Simulations of novel Compound Parabolic Concentrator (CPC) targets show the guiding and subsequent intensification of the laser light to increase the temperature of the accelerated electrons.

Principal Investigator: Andrew MacKinnon

LDRD Project: Establishing a Laser-Driven Megaelectronvolt X-Ray and Neutron Radiographic Capability

Andrew MacKinnon, the project's principal investigator, is using these CPC targets for the project. "These experiments showed that miniature plasma mirror targets do improve coupling of petawatt-class lasers to MeV (mega-electronvolt) electrons, which benefits potential applications such as laser-based MeV radiography," he said.

The team used the Texas petawatt laser system at the University of Texas at Austin during a six-week period, which has a short pulse and high contrast that allowed the experiment to work. The target is a compound CPC that is specifically designed to focus more laser energy on the tip and increase the intensity.

The Department of Energy's Office of Science supported the LaserNetUS initiative at Texas Petawatt and LLNL's Laboratory Directed Research and Development program funded the team and the crucially important target development from General Atomics.

The team has been awarded additional time through LaserNetUS at the Texas petawatt to continue research on CPCs targets, concentrating on the acceleration of the protons from the rear surface and the enhancement that the CPCs provide.

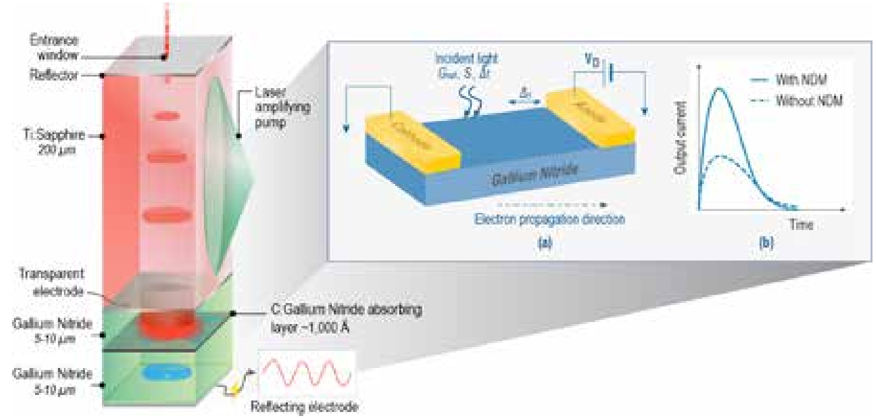
LLNL and UIUC collaborators design semiconductor switch for next-generation communications

An LDRD-funded team of engineers at LLNL designed a new kind of laser-driven semiconductor switch that can theoretically achieve higher speeds at higher voltages than existing photoconductive devices. The development of such a device could enable next-generation satellite communication systems capable of transferring more data at a faster rate, and over longer distances, according to the research team.

Scientists at LLNL and the University of Illinois Urbana-Champaign (UIUC) reported on the design and simulation of the novel photoconductive device in a paper published in the IEEE Journal of the Electron Devices Society. The

Principal Investigator: Lars Voss

LDRD Project: Compact High Efficiency Electrically Tunable Amplifier (CHEETAh)



Lawrence Livermore National Laboratory engineers have designed a new kind of laser-driven semiconductor switch that can theoretically achieve higher speeds at higher voltages than existing photoconductive devices. If the device could be realized, it could be miniaturized and incorporated into satellites to enable communication systems beyond 5G, potentially transferring more data at a faster rate and over longer distances, according to researchers.

device utilizes a high-powered laser to generate an electron charge cloud in the base material gallium nitride while under extreme electric fields.

Unlike normal semiconductors, in which electrons move faster as the applied electrical field is increased, gallium nitride expresses a phenomenon called negative differential mobility, where the generated electron cloud doesn't disperse, but slows down at the front of the cloud. This allows the device to create extremely fast pulses and high voltage signals at frequencies approaching one terahertz when exposed to electromagnetic radiation, researchers said.

Funded by the LDRD program, the project aims to demonstrate a conduction device that can operate at 100 GHz and at a high power. Future work will examine the impact of heating from the laser on the electron charge cloud, as well as improving understanding of the device's operation under an electrical–optical simulation framework.

"The goal of this project is to build a device that is significantly more powerful than existing technology but also can operate at very high frequencies," said LLNL engineer and project principal investigator Lars Voss. "It works in a unique mode, where the output pulse can actually be shorter in time than the input pulse of the laser—almost like a compression device. You can compress an optical input into an electrical output, so it lets you potentially generate extremely high speed and very high-power radio frequency waveforms."

"If the photoconductive switch modeled in the paper could be realized, it could be miniaturized and incorporated into satellites to enable communication systems beyond 5G, potentially transferring more data at a faster rate and over longer distances," Voss said. To further optimize performance, researchers are exploring other materials for testing.

Intellectual Property

Year after year, projects sponsored by LDRD achieve a disproportionately large percentage of the patents and copyrights issued for LLNL research. As illustrated in the following tables, in recent years LDRD-funded work has been key in developing more than half of the Laboratory's patents, one-third of the Laboratory's copyrights (chiefly computer code), and more than half of the Laboratory's records of invention.

Patents	FY17	FY18	FY19	FY20	FY21
All LLNL patents	88	79	143	200	166
LDRD patents	55	41	95	131	96
LDRD patents as a percentage of total	63%	52%	66%	66%	58%

Copyrights	FY17	FY18	FY19	FY20	FY21
All LLNL copyrights	105	105	118	138	125
LDRD copyrights	19	23	24	31	42
LDRD copyrights as a percentage of total	18%	22%	20%	22%	34%

Records of Invention	FY17	FY18	FY19	FY20	FY21
All LLNL records	110	105	129	126	89
LDRD records	53	47	65	56	53
LDRD records as a percentage of total	48%	45%	50%	44%	60%

LDRD-funded work has played a key role in developing

MORE THAN 50%

of the Laboratory's patents.

Building on LDRD research to create groundbreaking 3D metal-printing technology

Developed by an industrial partnership between LLNL and Seurat Technologies Inc. of Wilmington, Massachusetts, the technology, called Large-Area Pulsed Laser Powder Bed Fusion (LAPBF) Area Printing™, has the potential to revolutionize metal additive manufacturing (AM). Companies requiring larger metal parts, such as aerospace and automotive manufacturers, are among the industries that could benefit from industrial metal printers with unparalleled speed and resolution.

Principal Investigator: Manyalibo Matthews

LDRD Project: A New Science-Based Paradigm Enabling Microstructure-Tailored Additive Manufacturing of Metals

Examples of precision 3D-printed stainless steel using Seurat's patented additive manufacturing Area Printing technology.

The technologies enabling Area Printing were developed by Seurat's CEO, former LLNL researcher James DeMuth, and several LLNL colleagues—some of whom have also gone on to work at Seurat. The company derives its name from the post-impressionist painter Georges Seurat, who studied the science of light and pioneered the painting style known as pointillism.

The path that took DeMuth from a master's degree in engineering to the verge of launching a groundbreaking new manufacturing technology led through two crucial LDRD projects. After DeMuth joined LLNL and helped design the reaction chamber for an inertial fusion energy (IFE) powerplant, he and his colleagues determined that the only material able to handle the 600°C (1,100°F) heat and rapid temperature fluctuations without cracking was a steel-nanoparticle composite able to maintain its strength at high temperatures.

The researchers concluded that the only process capable of producing the specialized parts for the reactor was a type of additive manufacturing called laser powder bed fusion (L-PBF). Also known as selective laser melting, L-PBF works by shining a laser onto a thin layer of metal powder; the intense laser spot melts the powder and welds it to the layer below.

In 2013, LLNL's Directed Research and Development (LDRD) program funded a strategic initiative to develop diode-based additive manufacturing (DiAM), an L-PBF technique that can flash-print an entire layer of metal powder at a time. The DiAM research was led by Chris Spadaccini, Bassem El-Dasher, and DeMuth. Using high-powered arrays of laser diodes, a Q-switched (pulsed) laser, and the optically addressable light valve (OALV), DiAM was able to 3D-print metal objects faster than ever before.

A follow-on LDRD program led by LLNL scientist Ibo Matthews funded wide-area photolithographic printing research. The Lab's Gabe Guss and Reggie Drachenberg played a central role in producing the parts for the project, with contributions from Josh Kuntz and Eric Duoss.

DeMuth recognized that the information gained in the LDRD projects had broad applications to industry. The ability to design and produce additively manufactured metal parts with tailored microstructures that meet stringent performance requirements were crucial.

"This system demonstrated that we could project laser light down to a bed of metal powder, weld a patterned area in an instant, and build a multi-layer part using this technique," DeMuth writes. "This system architecture was the solution, opening endless possibilities for additive manufacturing."

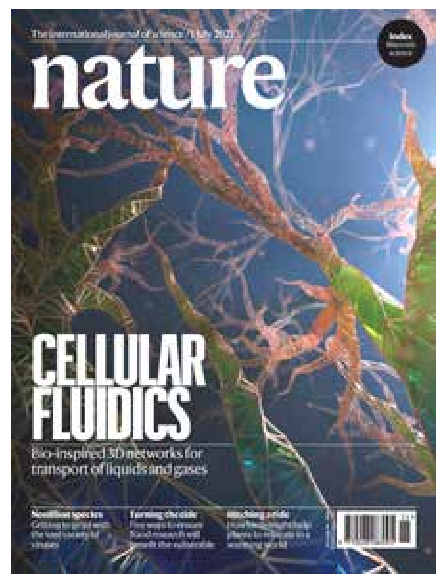
Scientific Publications

Laboratory scientists and engineers publish more than a thousand papers each year in a wide range of peer-reviewed journals, of which LDRD-funded work accounts for a large portion. The numerous publications made possible through LDRD-sponsored research help the Laboratory maintain a strong presence in the broader scientific community, extending the impact of LDRD research beyond the DOE mission space into the wider scientific arena. In addition, the impact of these publications documenting LDRD project results extends long after articles appear in the journals, increasing the value of LDRD investments in these projects.

Journal Articles	FY17	FY18	FY19	FY20	FY21
All LLNL articles	1,126	1,178	1,281	1,149	1,256
LDRD articles	274	456	553	428	509
LDRD articles as a percentage of total	24%	39%	43%	37%	41%

Principal Investigator: Eric Duoss

LDRD Project: Manufacturing Molecules for the New Carbon Economy



Inspired by the way plants absorb and distribute water and nutrients, LLNL researchers developed a groundbreaking method for transporting liquids and gases using 3D-printed lattice design and capillary action phenomena.

In a paper published in Nature and featured on the publication's cover, LLNL researchers describe 3D-printed micro-architected structures capable of containing and flowing fluids to create extensive and controlled contacts between liquids and gases. The ordered, porous, and open-cell structures facilitate surface tension-driven capillary action (the movement of liquid though small pores due to adhesion and cohesion forces) in the unit cells—akin to a tree pulling water from soil or a paper towel soaking up a spill—and enable liquid and gas transport throughout the structures.

"The problem with these complex environments is that we haven't had a good way to create model systems to facilitate understanding the fundamental science. For example, we can't yet make artificial lungs, where you have this complexity of having gases, liquids, and solids co-present," said Eric Duoss, director of LLNL's Center for Engineered Materials and Manufacturing and LDRD principal investigator. "But now what we have is a platform to do those fundamental studies that are so important for creating understanding."

Principal Investigator: Kimberly Knight

LDRD Project: Identifying the Influence of Environmental Effects on Post-Detonation Chemistry and Debris Formation

An LDRD project team has taken a closer look at how nuclear weapon blasts close to the Earth's surface create complications in their effects and apparent yields. Attempts to correlate data from events with low heights of burst revealed a need to improve the theoretical treatment of strong blast waves rebounding from hard surfaces.

This led to an extension of the fundamental theory of strong shocks in the atmosphere, which was first developed by G.I. Taylor in the 1940s. The work represents an improvement to the Lab team's basic understanding of nuclear weapon effects for near-surface detonations. The results indicate that the shock wave produced by a nuclear detonation continues to follow a fundamental scaling law when reflected from a surface, which enables the team to predict detonation-related damage more accurately in a variety of situations.

The findings, featured in Proceedings A of the Royal Society Publishing, are authored by Andy Cook, Joe Bauer, and Greg Spriggs. The work, "The Reflection of a Blast Wave by a Very Intense Explosion," was also highlighted on the cover of the publication.

Early Career Opportunities: Students and Postdoctoral Fellows

By funding exciting, potentially high-payoff projects at the frontiers of science, the LDRD program attracts top talent in new and emerging fields of science and technology. As shown in the following tables, LDRD investments contribute to the health and robustness of LLNL's student and postdoctoral researcher programs.

Students	FY17	FY18	FY19	FY20	FY21
Students supported by LDRD	127	138	160	101	136
Percentage of all students	22%	22%	23%	18%	24%

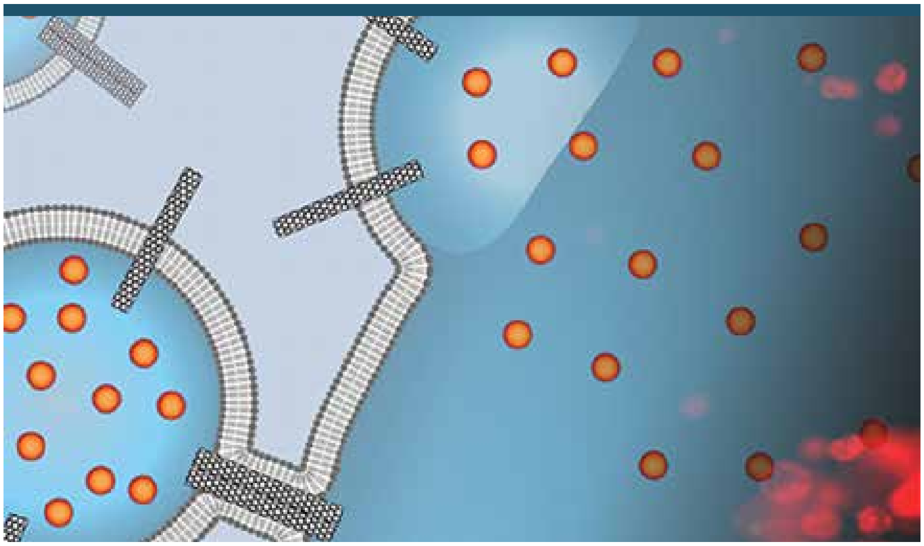
Postdoctoral Researchers	FY17	FY18	FY19	FY20	FY21
Postdoctoral researchers supported by LDRD ≥10% of their time	137	167	170	208	208
Percentage of all postdoctoral researchers	44%	54%	57%	63%	54%
LDRD postdoctoral researchers converted to full staff	31	52	46	60	50
Percentage of all conversions	53%	71%	68%	77%	81%

Summer students and postdoctoral researchers collaborate on direct drug delivery with carbon nanotube porins

Modern medicine relies on an extensive arsenal of drugs to combat deadly diseases such as pneumonia, tuberculosis, HIV-AIDS, and malaria. But getting those drugs into disease-ridden cells has remained a major challenge for modern pharmacology and medicine. To address this pressing need, career scientists, postdoctoral researchers, and summer students from LLNL, the University of California Merced, and the Max Planck Institute of Biophysics collaborated on the use of carbon nanotubes to enable direct drug delivery from liposomes through the plasma membrane into the cell interior by facilitating fusion of the carrier membrane with the cell.

Drugs are often poorly soluble, strongly toxic to other tissues, or face rapid degradation in the different chemical environments in an organism. They can accumulate in non-target tissues, bind to other cellular components, or may not internalize efficiently into the target cells.

Liposomal delivery systems aim to mitigate these problems by encapsulating drugs in external carriers that circulate through the bloodstream. However, these systems involve a trade-off between enhancing liposomal stability on the way to the target and easing payload release into the cytosol of the target cell.



The image is a montage of an artist's depiction of a liposomal drug carrier studded with carbon nanotube porins that is docking to a cancer cell surface and delivering chemotherapy cargo with a fluorescence microscopy image of stained cells exposed to these carriers. The red stain indicates that the cells are dead, and the treatment was successful. Images by P. Lastrico of MPI and N.T. Ho and A. Noy of LLNL.

Principal Investigator: Aleksandr Noy

LDRD Project: Longitudinal Monitoring of Ribonucleic Acid Content of a Live Cell with a Nanotube Pore Interface

"We thought that carbon nanotube porins—short pieces of carbon nanotubes inserted into lipid membranes—can mimic viral fusion peptide functionality and help to fuse the liposomal carriers to the membranes of cancer cells," said scientist Aleksandr Noy, who led the LLNL team.

In a series of experiments, the team demonstrated that a simple nanomaterial platform—a dimer of small-diameter carbon nanotube porins (CNTPs)—functions as a potent promoter of membrane fusion. Moreover, when Noy and his team loaded their liposomes with a potent chemotherapeutic agent (doxorubicin), these carriers delivered the drug to cancer cells, killing most of them.

"Our results open an avenue for simple and efficient drug delivery carriers compatible with a wide range of therapeutics," said Nga Ho, LLNL postdoctoral researcher.

Coarse-grained molecular dynamic simulations, performed by the team at Max Planck, revealed a distinct and unusual fusion mechanism where CNTP dimers tether the vesicles, pull the membranes into proximity, and then fuse their outer and inner leaflets.

"We were very happy to see that membrane fusion facilitated by small diameter carbon nanotube porins can lead to complete mixing of the membrane material and vesicle interior content," said Marc Siggel, a graduate student at Max Planck.

Collaborating across institutions and career stages, the co-researchers on this LDRD-funded project understood the potential significance of their work. With new ways to bypass the endocytic pathway, an improved drug delivery strategy could open new doors to therapeutic treatments.

Professional Fellows

One relevant indicator of advancement and leadership in a scientific field is the election of individuals as fellows of professional societies. This indicator reflects success for both the individual researcher and the Laboratory as a whole.

American Physical Society (APS) fellowships are awarded based on scientific merit and impact over an extended period, and the evaluation process relies on nomination and recommendation by peers. As such, data regarding the history of APS fellowships awarded to LLNL physicists provide an important indicator regarding the key role that the LDRD Program plays in developing the technical, scientific, and leadership skills of early career staff. As presented in the following table, for fiscal year 2021, 100% of the new APS Fellows from LLNL have early career LDRD experience.

Because the quantity of awards each year is a small number, we also present multi-year statistics. For example, over the last 20 years, more than 90% of the APS Fellows at LLNL had early career LDRD experience.

HISTORY OF APS FELLOWS AT LLNL

	Single-Year Statistics			Multi-Year Statistics		
	FY19	FY20	FY21	FY11–15 (5 yrs)	FY16–20 (5 yrs)	FY00–21 (21 yrs)
Total APS awards	6	4	3	25	21	97
Awards with LDRD roots	5	4	3	24	20	90
% with LDRD roots	83%	100%	100%	96%	95%	93%
Average years from first LDRD experience	15.6	20.8	17	13.6	18.2	12.8

TRACING IMPACT TO LDRD ROOTS

Throughout this section, we mention "LDRD roots." Much discussion with principal investigators has transpired about what it means for an accomplishment to have LDRD roots. A simple case would be if an idea for an invention arises during an LDRD project and work on the invention is completed during the period of LDRD investment. But R&D often does not advance on such a short timescale. In general, an accomplishment (invention, paper, capability, etc.) is determined to have LDRD roots if at least one LDRD project needed to occur for the accomplishment to take place. In other words, if one can identify an LDRD project that was critical to the accomplishment, then it is considered to have LDRD roots.

2021 APS Fellows at LLNL

Four LLNL scientists were selected as 2020 fellows of the American Physical Society. These new fellows represent a range of physics expertise, including laser-plasma physics, magnetic-fusion plasmas, condensed-matter physics, and theoretical and computational understanding of plasma interactions.

FELLOWS

TILO DOEPPNER

"I am incredibly honored and grateful to be selected as an APS fellow. It is humbling to be recognized by my peers in the plasma physics community."

Tilo Doeppner, a physicist in the High Energy Density Division of the National Ignition Facility & Photon Science (NIF&PS) Directorate, was chosen for "pioneering new regimes of warm dense matter experimental science from megabar to gigabar pressures on high-energy lasers and light sources, relevant to understanding brown dwarf and white dwarf interiors and inertial confinement fusion science."

TAMMY MA

"I'm grateful to LLNL for all the opportunities, support, and great working relationships. I'm honored to receive this alongside Dr. Doeppner and Dr. Xu."

Tammy Ma, a physicist in the High Energy Density Division of the NIF&PS Directorate, was selected for "outstanding scientific contributions and leadership in the field of intense laser-matter interactions and inertial fusion energy science." At the Advanced Photon Technologies (APT) Program within NIF&PS, her team is working on high-intensity short-pulse laser-based research, with a focus on establishing new applications of these tools to support future National Nuclear Security Administration and Department of Energy missions.

XUEQIAO XU

"It is a great honor to be recognized as a fellow of the American Physical Society. I feel very proud, and I am most grateful to those nominating me and awarding me with such distinction."

Xueqiao Xu, a physicist in the Physics Division of the Physical and Life Sciences Directorate, was cited for "wide-ranging contributions to the understanding of the tokamak edge, including edge pedestal stability and the onset and evolution of edge localized modes and for leading the development of edge simulation models and codes." Xu has been at the Lab for 28 years and his research focuses on theory and simulations of boundary plasma turbulence and transport for physics research of magnetic fusion energy, such as ITER (International Thermonuclear Experimental Reactor).

Long-term Impact

The LDRD program is an investment in our nation's future, ensuring mission support that is often realized many years after an LDRD-funded project concludes. Recognizing this long-term impact of the LDRD program, we believe it is important to highlight indicators that span multiple years, demonstrating the true impact of LDRD as a national asset.

We collaborated with our colleagues from LDRD programs at other NNSA institutions to identify ways that we could best represent the long-term impact of LDRD investments. As each institution issues its LDRD program report for fiscal year 2021, we present a common set of long-term performance indicators including the content provided below.

Distinguished Member of the Technical Staff

One relevant indicator of career advancement in a science and technology field is the recognition of individuals as distinguished members of the technical staff at the institution. Individuals who receive this recognition are identified as being in the top 1% or 2% of the institution's scientific and technical staff, similar to a lifetime achievement award, or in this case, for their contribution to the Laboratory's mission.

At LLNL, appointment as a Distinguished Member of the Technical Staff (DMTS) is reserved for Laboratory scientists and engineers who have demonstrated a sustained history of high-level achievements in programs of importance to the Laboratory, become a recognized authority in the field, or made a fundamental and important discovery that has sustained, widespread impact.

As presented in the table on the following page, a vast majority of these distinguished staff at LLNL had early career experience with LDRD projects, which helped them develop their scientific, technical, and leadership skills.

HISTORY OF DMTS AWARDS AT LLNL						
	Single-Year Statistics			Multi-Year Statistics		
	FY19	FY20	FY21	FY11–15 (5 yrs)	FY16–20 (5 yrs)	FY11–20 (10 yrs)
Total DMTS awards	6	0	0	34	14	48
DMTS with LDRD roots	6	N/A	N/A	27	14	41
% with LDRD roots	100%	N/A	N/A	79%	100%	85%
Average years from first LDRD experience	17.5	N/A	N/A	18.1	21.1	19.1

R&D 100 Awards

Another indicator of advancement and leadership in a scientific field is the R&D 100 Award program, which honors the top innovations of the past year. R&D 100 Awards can occur a long time after the initial ideas are developed, often during LDRD projects. Typically, it takes 5 to 10 years (or longer) from concept development to receiving an R&D 100 award, including the time needed to move through patenting an invention and demonstrating its commercial applications.

The LDRD program is an investment in our nation's future, ensuring mission support that is often realized many years after an LDRD-funded project concludes. Recognizing this long-term impact of the LDRD program, we believe it is important to highlight indicators that span multiple years, demonstrating the true impact of LDRD as a national asset.

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OVER THE LAST 20 YEARS, approximately half of LLNL's R&D 100 Awards had roots in the LDRD Program.

HISTORY OF R&D 100 AWARDS AT LLNL

	Single-Year Statistics			Multi-Year Statistics		
	FY19	**FY20**	**FY21**	**FY12–16 (5 yrs)**	**FY17–21 (5 yrs)**	**FY12–21 (10 yrs)**
Total R&D 100 awards	4	1	3	21	15	36
Awards with LDRD roots	2	0	0	10	3	13
% with LDRD roots	50%	0%	0%	48%	20%	36%
Average years from first LDRD investment	12.0	N/A	N/A	6.9	11.0	7.9

The renowned R&D 100 competition, now in its 59th year, received entries from 17 countries and regions around the world.

Program Accomplishments

LDRD-funded research explores the frontiers of science and technology in emerging mission spaces, with projects guided by an extremely creative, talented team of scientists and engineers.

Featured Research

LDRD funded 263 projects in fiscal year 2021. Brief summaries of each project are included in the Project Highlights section of our online report at ldrd-annual.llnl.gov. Here, we provide a closer look at a handful of projects that underscore the exciting, innovative research in this year's LDRD portfolio.

Collaborating to develop a universal coronavirus vaccine

ConserV Bioscience Limited (CBL) and LLNL have agreed to collaborate on the development of a broad-spectrum or "universal" coronavirus vaccine.

This collaboration brings together CBL's expertise in identifying antigens and LLNL's nanolipoprotein delivery system. The vaccine has been designed to provide broad-spectrum protection against coronavirus pathogens of human and animal origin, including but not limited to MERS, SARS, and SARS-CoV-2 (the virus that causes COVID-19).

The vaccine construct consists of conserved immunoreactive regions from external and internal coronavirus proteins, from each virus genus, encoded in messenger RNA (mRNA). The mRNA construct will be formulated with LLNL's propriety nanolipoprotein particle vehicle (NLP) prior to injection, allowing freeze drying of both components separately to avoid cold chain storage and transport issues.

Coronaviruses are a group of single-stranded RNA viruses that, in humans, cause respiratory tract infections and other mild to lethal effects. In December 2019, a novel strain of coronavirus, SARS-CoV-2, was identified in Wuhan, China. To date, over 506 million people globally have been infected by the virus and more than 6.2 million individuals have died from the COVID-19 infection, though estimates suggest a higher range of 15-25 million deaths as data continue to be released.

The related LDRD project focuses on nucleic acid-based therapeutics with specially encoded proteins that promote the production of vaccine antigens. The versatile nanoplatform would drastically reduce the time from concept to administration of the therapeutic, providing a powerful defense against biological threats and disease.

"We are pleased to be working with the Biosciences and Biotechnology Division at LLNL to develop our broad-spectrum coronavirus vaccine candidate," said Kimbell Duncan, CEO of ConserV Bioscience. "We have identified regions within the proteins of the virus that are not susceptible to change and if effective, the vaccine promises to protect against a broad spectrum of current circulating coronavirus strains and future emergent ones."

Added LLNL biologist Amy Rasley: "We look forward to combining our nanolipoprotein particle technology with ConserV's mRNA construct

LLNL researchers Nicholas Fischer and Amy Rasley are characterizing nanolipoprotein particle vaccine formulations using a dynamic light-scattering instrument. Detailed characterization of the nanoparticles provides an important quality control metric for vaccine development. A United Kingdom company, ConserV Bioscience Limited, and LLNL have agreed to work on developing a universal coronavirus vaccine. Photo by Julie Russell/LLNL (taken pre-pandemic).

Principal Investigator: Nicholas Fischer

LDRD Project: Delivering Ribonucleic Acid Vaccines Using Nanoparticles

encoding conserved viral epitopes. We hope to advance the vaccine candidate to human trials as quickly as possible."

Rasley's fellow principal investigator on the project, Nicholas Fischer, noted: "Our NLP technology is very versatile, so we anticipate that we can tune our platform formulation to produce safe and effective vaccine candidates."

Natural variations help resolve a climate puzzle

New research shows that naturally occurring climate variations help to explain a long-standing difference between climate models and satellite observations of global warming.

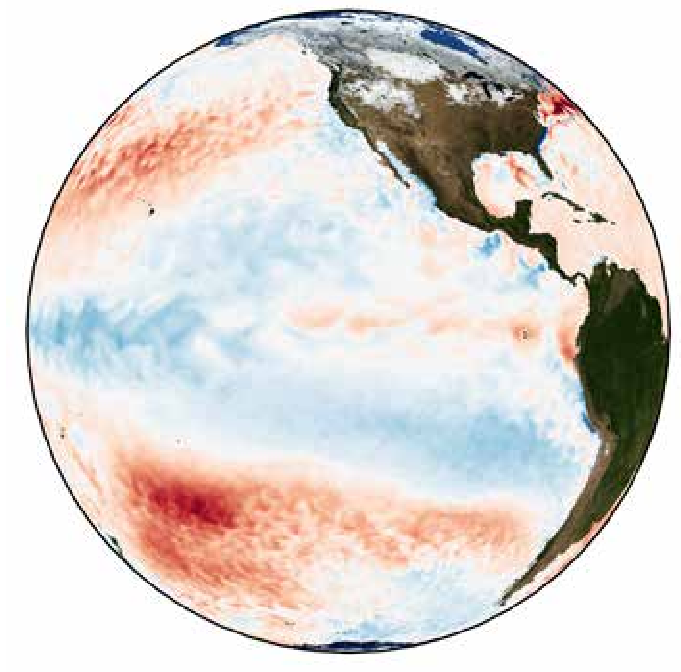
Satellite measurements of global-scale changes in atmospheric temperature began in late 1978 and continue to the present. Relative to most model simulations, satellite data has consistently shown less warming of Earth's lower atmosphere. This has led some researchers to conclude that climate models are too sensitive to greenhouse gas emissions, and thus are not useful for making future climate change projections.

Instead, the model-versus-satellite difference is largely driven by natural variations in the Earth's climate. "Natural climate variability has likely reduced the observed warming during the satellite-era" said Stephen Po-Chedley, the project's principal investigator and lead author of a related paper appearing in the Proceedings of the National Academy of Sciences.

The main driver of natural year-to-year variations in global climate is the El Niño-Southern Oscillation (ENSO). Many climate models produce ENSO variations, but the timing of these events is not specified in model

Principal Investigator: Stephen Po-Chedley

LDRD Project: Advancing Measurements and Understanding of the Rate and Structure of Atmospheric Warming



Sea surface temperature anomalies illustrating the current La Niña event (courtesy of NOAA Coral Reef Watch) blended with the NASA January Blue Marble image.

simulations. “While models are intended to represent the average climate, its changes and realistic natural variations, they can only simulate the exact timing of natural climate events by chance,” said Po-Chedley.

Some decades favor El Niño or La Niña events, and clustering can create decadal oscillations that influence the rate of atmospheric warming. Simulations with coupled models of the atmospheric and ocean circulation produce such decadal oscillations, but their phasing will not necessarily match the real world during the satellite era.

The researchers analyzed hundreds of simulations from the newest generation of global climate models. They found that natural climate variability is a key component of the differences between modeled and observed warming rates. Roughly 13 percent of the 400-plus simulations showed warming of the tropical troposphere within the range of satellite results. The model simulations that agree with the satellite record tend to exhibit a La Niña-like temperature change pattern, just like the observations.

Such agreement yields two important findings. First, despite claims to the contrary, current climate models can simulate warming of the tropical troposphere that is consistent with observations. Second, natural variability has likely reduced tropospheric warming over the satellite era, both in the real world and in simulations consistent with satellite warming rates.

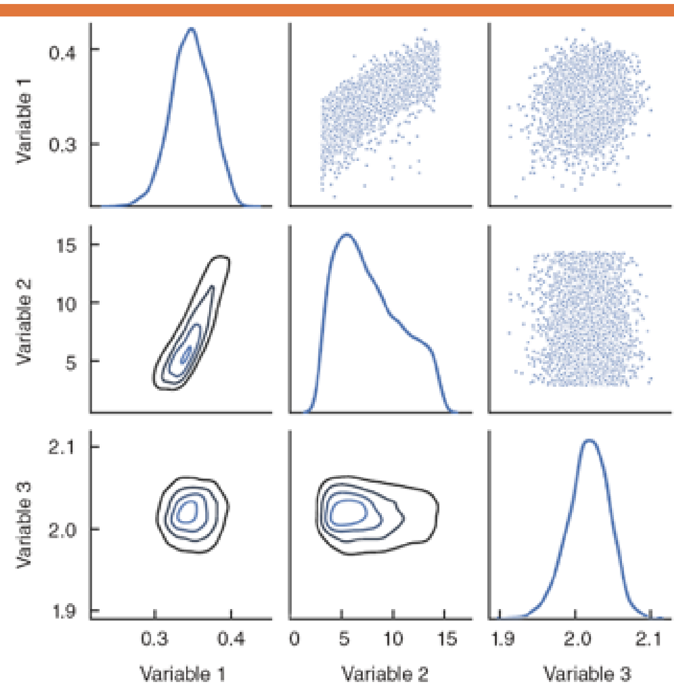
Another significant finding of the study relates to the suggestion that differences between modeled and observed warming rates are due to errors in “climate sensitivity”—the size of the warming in response to increases in greenhouse gases.

"Models with both high and low sensitivity to greenhouse gas increases can produce simulations consistent with the warming estimated from satellites," Po-Chedley said. "In reconciling modeled and observed warming rates, it's pretty clear from our work that climate sensitivity is not the sole determinant of atmospheric warming. Natural variability is an important piece in the puzzle."

Quantifying uncertainties in material strength research to benefit experimental planning

The best way to understand how a material behaves under certain conditions is to test it. For example, an engineering project may rely on understanding a material's strength—its resistance to permanent deformation—across a range of temperatures and strain rates. Gathering all relevant experimental data could be challenging or even impossible due to the time and cost required, material availability, or the difficulty of recreating certain conditions in a laboratory setting. Researchers, therefore, rely on models informed by available data to predict the performance of materials at untested conditions.

LLNL has a vested interest in understanding the accuracy of these models and the data that feed them. Material property models play a foundational



The posterior distribution—the outcome of Bayesian calibration—quantifies the state of knowledge about the model parameters given the experimental data and the choice of the prior distribution. In these plots of posterior distribution based on dynamic tantalum experiments, the probability distributions on the diagonal represent the marginal posterior distributions for each parameter: the narrower the distribution, the more certain researchers can be of the parameter value. The off-diagonal pairwise plots, shown with two different plotting types above and below the diagonal, illustrate the correlations between the variables. In this example, Variables 1 and 2 have a stronger correlation compared to the other pairings as observed with the linear-like grouping with a positive slope in the corresponding off-diagonal plots, which indicates a positive correlation.

Principal Investigator: Jeff Florando

LDRD Project: Understanding Material Strength Variabilities and Uncertainties for Component Qualification role in a range of Livermore's science and engineering research endeavors including stockpile stewardship, the National Nuclear Security Administration's program to ensure the safety and reliability of the nation's nuclear stockpile.

Materials modeler Nathan Barton explains, "As we shift manufacturing and design approaches to more modern methods, we need to quantify uncertainty to maintain confidence in our nuclear stockpile and our stockpile modernization activities. Understanding the uncertainties gives us increased confidence in the experimental results and the models informed by the experimental data."

Led by materials scientist Jeff Florando and supported by the LDRD program, Barton and other Laboratory statisticians, computational modelers, and materials scientists have been developing a statistical framework for researchers to better assess the relationship between model uncertainties and experimental data. In an earlier effort, Florando helped build the Material Implementation, Database, and Analysis Source (MIDAS), a central repository for material strength-related data and models. "My role in developing MIDAS helped me realize we needed to do a better job understanding uncertainties in material strength research," says Florando. "MIDAS helps us create material strength model parameterizations, but the simulations are deterministic—they give us an answer that is based on the parameters we put in them."

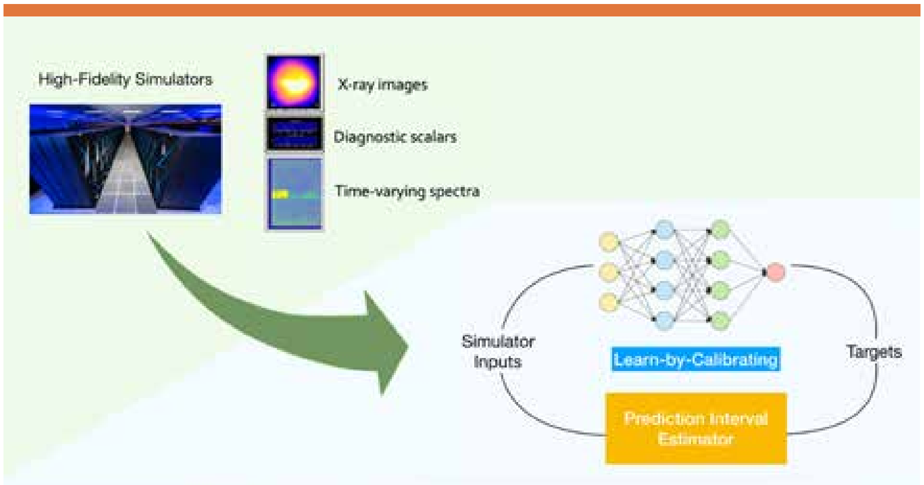
The latest framework, based on Bayesian methodology, allows for uncertainties to be updated as new and different types of strength data become available and can be used to determine the future experiment with the greatest potential to reduce uncertainty. Methods developed by the team have informed experimental planning efforts within the Laboratory's Weapons and Complex Integration (WCI) organization as well as research ventures exploring how materials evolve and degrade.

Exploring "learn-by-calibration" to emulate scientific process in deep learning

While there has been a surge in using machine learning to build data-driven emulators, the field has lacked an effective method for determining how closely the predictive models reflect physical reality. LLNL computer scientists have developed a new deep learning approach to designing emulators for scientific processes that is more accurate and efficient than existing methods.

In a paper published by Nature Communications, an LDRD research team describes a "Learn-by-Calibrating" (LbC) method for creating powerful scientific emulators that could be used as proxies for far more computationally intensive simulators. While it has become common to use deep neural networks to model scientific data, an often overlooked, yet important, problem is choosing the appropriate loss function—measuring the discrepancy between true simulations and a model's predictions—to produce the best emulator, researchers said.

The LbC approach is based on interval calibration, which has been used traditionally for evaluating uncertainty estimators, as a training objective to build deep neural networks. Through this novel learning strategy, LbC can



An LLNL team has developed a "Learn-by-Calibrating" method for creating powerful scientific emulators that could be used as proxies for far more computationally intensive simulators. Researchers found the approach results in high-quality predictive models that are closer to real-world data and better calibrated than previous state-of-the-art methods. Illustration courtesy of Jayaraman Thiagarajan/LLNL.

effectively recover the inherent noise in data without the need for users to pick a loss function.

Applying the LbC technique to various science and engineering benchmark problems, the researchers found the approach results in high-quality predictive models that are closer to real-world data and better calibrated than previous state-of-the-art methods. By demonstrating the technique on scenarios with varying data types and dimensionality, including a reservoir modeling simulation code and inertial confinement fusion (ICF) experiments, the team showed it could be broadly applicable to a range of scientific workflows and integrated with existing tools to simplify subsequent analysis.

"This is an extremely easy-to-use principle that can be added as the loss function for any neural network that we currently use, and make the emulators significantly more accurate," said lead author Jay Thiagarajan. "We considered different types of scientific data—each of these data have completely different assumptions, but LbC could automatically adapt to those use cases. We are using the same exact algorithm to approximate the underlying scientific process in all these problems, and it consistently produces much better results."

Analyzing microbiome profiles to support military readiness and performance

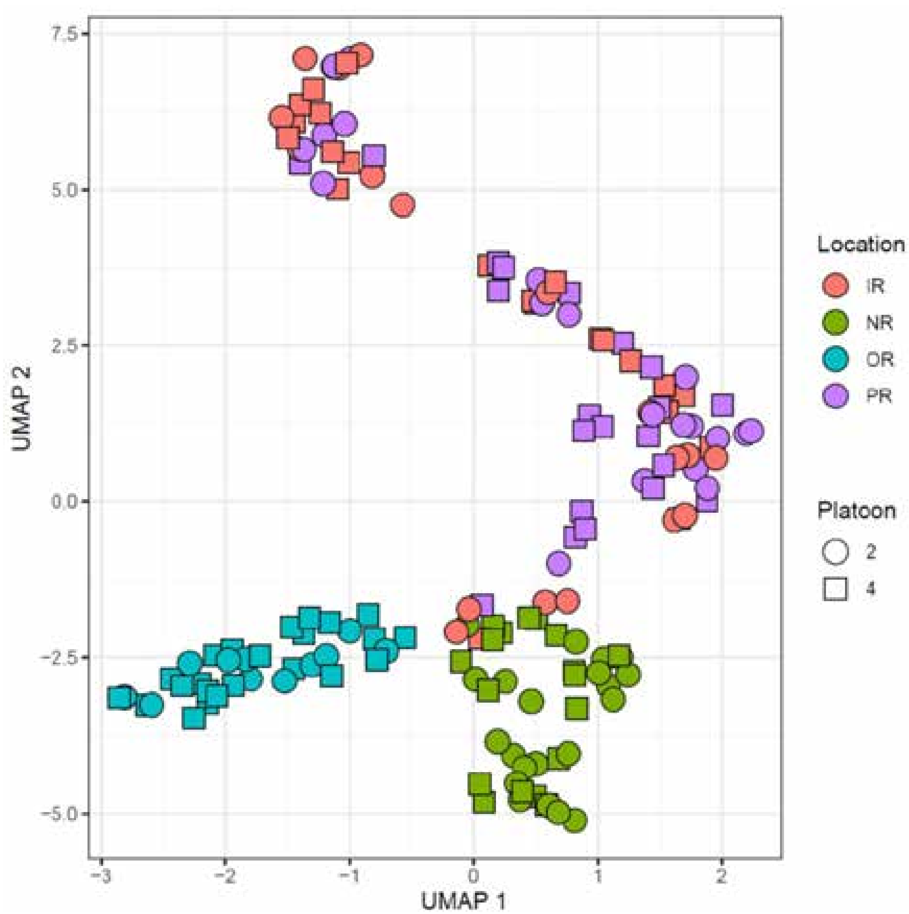
The human body serves as host to trillions of microorganisms, collectively known as the microbiome. In particular, the gastrointestinal tract contains a diverse and active microbial ecosystem, also known as a microbiota. The composition and activity of gut microbes are modulated by changes in host diet and physiology while, in turn, gut microbes support the immune system, regulate the central nervous system, and provide nutrients. This relationship is largely beneficial but remains delicate. The microbiome can easily be altered by environmental stressors, leading to a higher risk of

Principal Investigator: Jayaraman Thiagarajan

LDRD Project: Knowledge-Driven Machine Learning

Principal Investigator: Nicholas Be

LDRD Project: Boot Camp Bugs: Microbiomes of U.S. Infantry Trainees



Metagenomic sequencing was used to determine the microbial profile of each sample. Samples were obtained from multiple body sites ("Location") and separate platoons. The similarity between samples was evaluated using dimensionality reduction via UMAP (uniform manifold approximation and projection). Visualizing the data in this way allows for comparison of microbiome patterns and shifts across individuals, time, body sites, and other parameters relevant to military trainees. This permits assessment of microbiome convergence/divergence in trainee communities, which could support future efforts relevant to military health and readiness.

systemic inflammation, increased susceptibility to illness, higher rates of infection, and the recurrence of chronic disease.

Military training places uniquely high demands on the physical and psychological health of soldiers. Individuals in training are at increased risk for infectious diseases that can interrupt training cycles and compromise operational readiness. By examining health and performance metrics, trainee microbiomes could offer crucial information.

An LDRD-funded project used whole metagenome sequencing to examine the human microbiome in a closed cohort of U.S. Army Infantry trainees over the duration of a training cycle. In a longitudinal fashion and across multiple body sites, a feasibility study successfully demonstrated detection and statistical analysis of microbiome profiles in a unique and challenging sample set. These results lay critical groundwork toward more expansive tracking of microbial factors that could be employed for supporting the health, readiness, and performance of future warfighters. The data from this feasibility study could have implications toward optimizing microbiome interventions such as pre/probiotic manipulation.

Experiments validate the possibility of helium rain inside Jupiter and Saturn

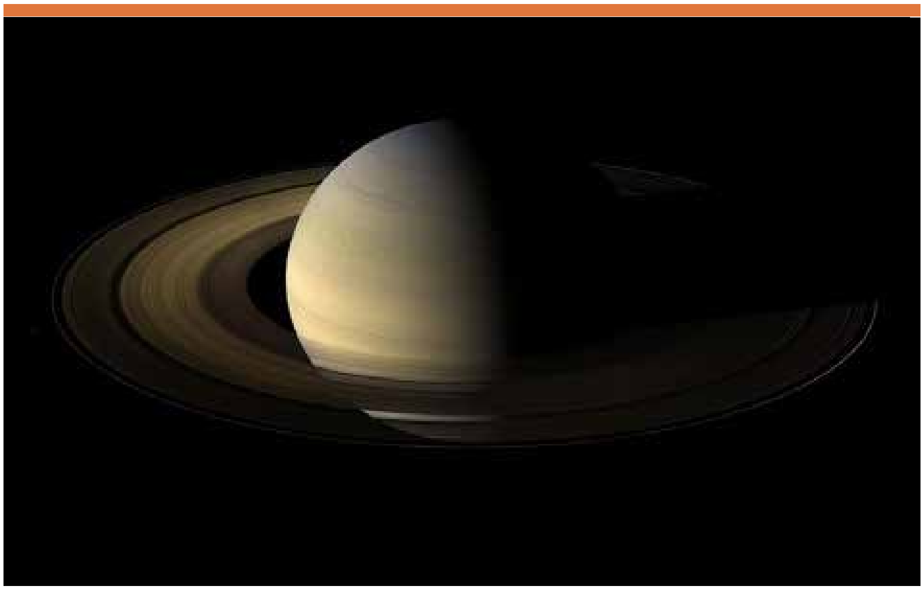
Nearly 40 years ago, scientists first predicted the existence of helium rain inside planets composed primarily of hydrogen and helium, such as Jupiter and Saturn. However, achieving the experimental conditions necessary to validate this hypothesis hasn't been possible—until now.

In a paper published by Nature, scientists reveal experimental evidence to support this long-standing prediction, showing that helium rain is possible over a range of pressure and temperature conditions that mirror those expected to occur inside these planets.

"We discovered that helium rain is real, and can occur both in Jupiter and Saturn," said Marius Millot, an LLNL physicist and LDRD principal investigator. "This is important to help planetary scientists decipher how these planets formed and evolved, which is critical to understanding how the solar system formed.

"Coupling static compression and laser-driven shocks is key to allow us to reach the conditions comparable to the interior of Jupiter and Saturn, but it is very challenging," Millot said. "We really had to work on the technique to obtain convincing evidence. It took many years and lots of creativity from the team."

The team used diamond anvil cells to compress a mixture of hydrogen and helium to 4 gigapascals, (GPa; approximately 40,000 times Earth's atmosphere). Then, the scientists used 12 giant beams of Laboratory for Laser Energetics Omega Laser to launch strong shock waves to further



An international research team, including scientists from Lawrence Livermore National Laboratory, has validated a nearly 40-year-old prediction and experimentally shown that helium rain is possible inside planets such as Jupiter and Saturn (pictured). Image credit: NASA/JPL/Space Science Institute.

Principal Investigator: Marius Millot

LDRD Project: Unraveling the Physics and Chemistry of Water-Rich Mixtures at Extreme Pressures and Temperatures compress the sample to final pressures of 60–180 GPa and heat it to several thousand degrees.

Using a series of ultrafast diagnostic tools, the team measured the shock velocity, the optical reflectivity of the shock-compressed sample, and its thermal emission, finding that the reflectivity of the sample did not increase smoothly with increasing shock pressure, as in most samples the researchers studied with similar measurements. Instead, they found discontinuities in the observed reflectivity signal, which indicate that the electrical conductivity of the sample was changing abruptly, a signature of the helium and hydrogen mixture separating.

"Our experiments reveal experimental evidence for a long-standing prediction: There is a range of pressures and temperatures at which this mixture becomes unstable and demixes," Millot said. "This transition occurs at pressure and temperature conditions close to that needed to transform hydrogen into a metallic fluid, and the intuitive picture is that the hydrogen metallization triggers the demixing."

Looking ahead, the team will continue to refine the measurement and extend it to other compositions in the continued pursuit of improving our understanding of materials at extreme conditions.

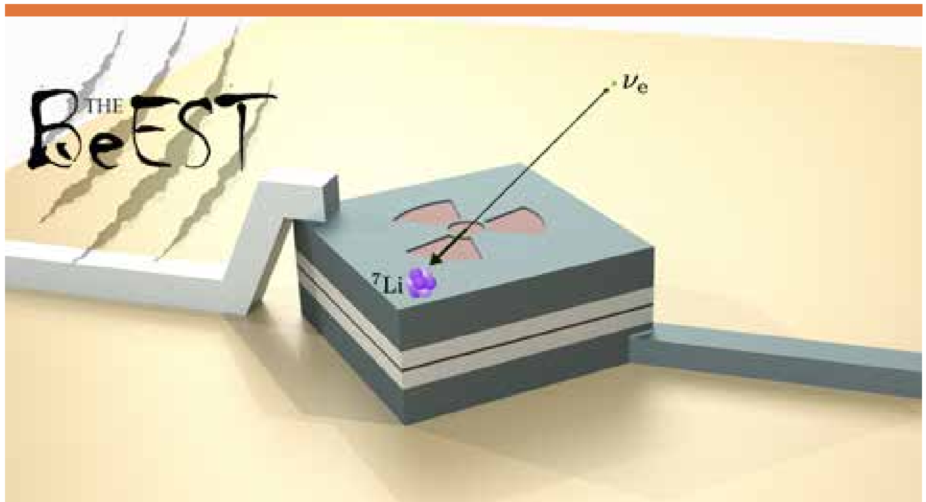
Using nuclear decay in the search for sterile neutrinos

"Sterile neutrinos" are theoretically predicted new particles that offer an intriguing possibility in the quest for understanding the dark matter in our universe. Unlike the known "active" neutrinos in the Standard Model (SM) of particle physics, these sterile neutrinos do not interact with normal matter as they move through space, making them very difficult to detect.

A team of interdisciplinary researchers, led by LLNL and the Colorado School of Mines, has demonstrated the power of using nuclear decay in high-rate quantum sensors in the search for sterile neutrinos. The findings

Principal Investigator: Stephan Friedrich

LDRD Project: A Search for Sterile Neutrino Dark Matter



Schematic of the "BeEST" experiment. Radioactive beryllium-7 is implanted into the superconducting sensor. Precision measurements of the decay products could indicate the presence of hypothesized sterile neutrinos.

are the first measurements of their kind.

The research has been featured recently as a DOE Office of Science Highlight and will jump-start an extended project to look for one of the most promising candidates for dark matter, the strange unidentified material that permeates the universe and accounts for 85 percent of its total mass.

The experiment involves implanting radioactive beryllium-7 atoms into superconducting sensors developed at LLNL and has been nicknamed the "BeEST" for "Beryllium Electron-capture with Superconducting Tunnel junctions." When the beryllium-7 decays by electron capture into lithium-7 and a neutrino, the neutrino escapes from the sensor, but the recoil energy of the lithium-7 provides a measure of the neutrino mass. If a heavy sterile neutrino with mass mc2 were to be generated in a fraction of the decays, the lithium-7 recoil energy would be reduced and produce a measurable signal, even though the elusive neutrino itself is not detected directly.

With a measurement time of just 28 days using a single sensor, the data exclude the existence of sterile neutrinos in the mass range of 100 to 850 kiloelectronvolts down to a 0.01 percent level of mixing with the active neutrinos—better than all previous decay experiments in this range. In addition, simulations on LLNL supercomputers have helped the team understand some of the materials effects in the detector that need to be accounted for to gain confidence in potential sterile neutrino detection events.

"This research effort lays the groundwork for even more powerful searches for these new particles using large arrays of sensors with new superconducting materials," said LLNL scientist Stephan Friedrich. "Sterile neutrinos are exciting because they are strong candidates for so-called 'warm' dark matter, and they also may help to address the origin of the matter–antimatter asymmetry of the universe," Friedrich said.

Determining planetary formation location via isotopic signature

As the solar system was developing, the giant planets (Jupiter and Saturn) formed very early, and as they grew, they migrated both closer to and further away from the sun to stay in gravitationally stable orbits.

The gravitational effect of these massive objects caused immense reshuffling of other planetary bodies that were forming at the time, meaning that the current locations of many planetary bodies in our solar system are not where they originally formed.

An LLNL team set out to reconstruct these original formation locations by studying the isotopic compositions of different groups of meteorites that all derived from the asteroid belt (between Mars and Jupiter). The asteroid belt is the source of almost all of Earth's meteorites, but the material that makes up the asteroid belt formed from sweeping of materials all over the solar system.

"If we want to know what the solar system looked like at inception, we need a tool to reconstruct this primordial structure," said LLNL cosmochemist and LDRD principal investigator Greg Brennecka. "We've

Principal Investigator: Greg Brennecka

LDRD Project: Addressing Unresolved Questions About the Solar System with New Lunar Samples from the Apollo Missions

LLNL researchers have found that the current locations of many planetary bodies in the solar system are not where they originally formed. Image courtesy of NASA.

found a way to use isotopic signatures in meteorites to reconstruct what the solar system looked like when it was formed."

Even though the asteroid belt is only a relatively narrow band of the solar system, it contains an impressively diverse collection of materials. For example, multiple spectroscopically distinct asteroid families have been identified within the main belt, indicating vastly different chemical compositions. In addition, meteorites are known to derive from roughly 100 distinct parent bodies in the belt, with diverse chemical and isotopic signatures.

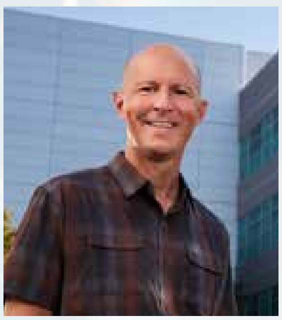
Tracing the source material of planetary bodies requires signatures that are established during planetary body accretion. Isotopic anomalies of nucleosynthetic origin represent powerful tools because these signatures fingerprint the actual building material from which these planetary bodies accreted.

The team took samples of basaltic achondrites (stony meteorites similar to terrestrial basalts) to measure their nucleosynthetic isotope signatures in the elements neodymium (Nd) and zirconium (Zr). Their work showed that these elements are characterized by relative deficits in isotopes hosted by a certain type of presolar material. The data are well correlated with nucleosynthetic signatures observed in other elements, demonstrating that this presolar material was distributed as a gradient throughout the early solar system. This research will also be expanded in a related LDRD-funded project investigating newly identified samples from the Apollo lunar sample collection to constrain the age, origin, and evolution of the Moon.

Scientific Leadership and Service

LDRD projects are distinguished by their mission-driven creativity. LDRD-funded research often launches stellar careers, initiates strategic collaborations, produces game-changing technical capabilities, and even lays the foundation for entirely new fields of science. It is no surprise that every year, LDRD principal investigators from LLNL are recognized for the groundbreaking results of a project or long-term contributions to their fields. The following examples highlight recognition received during fiscal year 2021, attesting to the exceptional talents of these researchers and underscoring the vitality of Livermore's LDRD program.

FELLOWS



ROB FALGOUT

Fellow, Society for Industrial and Applied Mathematics

The Society for Industrial and Applied Mathematics (SIAM) selected Livermore computational mathematician Rob Falgout as an esteemed member of its 2021 Class of SIAM Fellows. The prestigious honor recognizes Falgout, a Distinguished Member of the Technical Staff in LLNL's Center for Applied Scientific Computing, for his "contributions to the theory, practice and large-scale applications of multilevel solvers and for widely used parallel software," as well as his outstanding service to the community, according to the organization. Falgout is best known in the field of mathematics for his development of multigrid methods and for hypre, one of the world's most popular parallel multigrid codes.

"It's an incredible honor to be named a SIAM fellow and to be listed alongside such remarkably talented people."

CHRISTOPHER STOLZ

Fellow, SPIE, the International Society for Optics and Photonics

SPIE named Christopher Stoltz a fellow of the international society for optics and photonics in recognition of his technical achievement and his service to the general optics community. Stoltz, an associate program manager in charge of the National Ignition Facility (NIF) optics supply, has worked at LLNL in the laser directorate as a thin film engineer for more than 30 years; first in Atomic Vapor Laser Isotope Separation (AVLIS) and then NIF. Throughout his career, Stoltz has focused on understanding how micron scale and smaller defects limit the laser fluence in complex optical interference coating structures. Stolz helped pioneer the use of Ion Beam Sputtering (IBS) for high fluence pulsed-laser systems.

"I am very honored to be recognized by SPIE for not only my technical contributions to the laser program at LLNL, but also for my service to both SPIE and Optica (formerly OSA) conference leadership."

OTHER AWARDS

Secretary's Exceptional Service Award, Department of Energy

Administrator's Distinguished Service Gold Award, National Nuclear Security Administration

Former Lawrence Livermore National Laboratory director **Bill Goldstein** received honors from the Department of Energy and the National Nuclear Security Administration in recognition of his significant accomplishments as a scientist, leader in national security, and director of LLNL. In a virtual ceremony, then-acting Secretary of Energy David Huizenga conferred the Secretary's Exceptional Service Award to Goldstein in recognition of his "dedication and service to the National Nuclear Security Administration, the Department of Energy, and the nation."

Lifetime Distinguished Achievement Award, Department of Energy's Vehicle Technologies Office

Livermore engineer **William Pitz** has earned a lifetime distinguished achievement award from the Department of Energy's Vehicle Technologies Office for his significant contributions to the field of chemical kinetics. Pitz, along with retiree Charles Westbrook, produced a chemical kinetic study of fuel additives for engine knock in spark ignition engines, a feat that earned them the 1991 Horning Award from the Society of Automotive Engineers. Their area of research is the development of chemical kinetic mechanisms for conventional fuels like gasoline and diesel fuel, and also for next-generation fuels, such as new types of biofuels being considered as potential replacements for fossil fuels.

Mark Mills Award, American Nuclear Society

Dylan Hoagland was honored with the 2021 American Nuclear Society (ANS) Mark Mills award. The Mark Mills Award is conferred by the Education, Training and Workforce Division of the ANS and is presented every year to the graduate student author or authors who submit the best original technical paper contributing to the advancement of science and engineering related to the atomic nucleus.

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Edward Teller Award, American Nuclear Society

Omar Hurricane, chief scientist for Livermore's inertial confinement fusion (ICF) program, is a recipient of the 2021 Edward Teller Award. The Fusion Energy Division of the American Nuclear Society (ANS) presented the award to Hurricane for his "visionary scientific insights and leadership of National Ignition Facility (NIF) experiments resulting in the achievement of fuel gain, an alpha-heating-dominated plasma, and a burning plasma." Hurricane was elected a fellow of the American Physical Society in 2016 in recognition of these contributions to ICF leading to the first laboratory demonstration of an alpha-heating dominated plasma. Established in 1991, the Edward Teller Award recognizes pioneering research and leadership in the use of lasers, ion-particle beams, or other high-intensity drivers to produce unique high-density matter for scientific research and to conduct investigations of inertial fusion. The medal is named in honor in honor of the late distinguished LLNL director.

DOE Office of Science Early Career Research Program Award

Two LLNL scientists were among 83 individuals nationwide selected for the 2021 Department of Energy's (DOE) Office of Science Early Career Research Program award. The Early Career Research Program bolsters the nation's scientific workforce by providing support to exceptional researchers during crucial early career years, when many scientists do their most formative work. Under the program, typical awards for DOE national laboratory staff are $500,000 per year for five years.

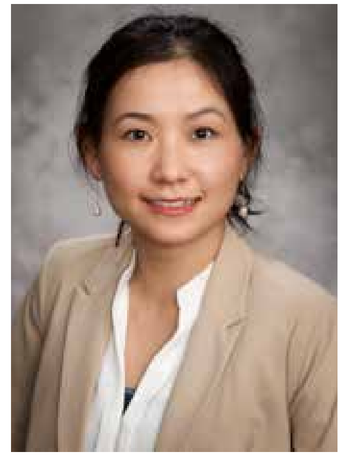
"Maintaining our nation's brain trust of world-class scientists and researchers is one of DOE's top priorities—and that means we need to give them the resources they need to succeed early on in their careers," Secretary of Energy Jennifer M. Granholm said. "These awardees show exceptional potential to help us tackle America's toughest challenges and secure our economic competitiveness for decades to come."

Andrea Schmidt, a physicist in the National Security Engineering Division in the Engineering Directorate, was nominated in the High Energy Density Physics category for her work in magnetically driven Z-pinch plasmas. These plasmas can be used to study fundamental plasma physics and to produce radiation of various types for different applications.

"It is an incredible honor to be chosen for this award," Schmidt said. "It will allow me to spend more time on discovery science over the next few years, and fund activities that are very complementary to my program work."

Schmidt joined the Lab as a postdoctoral researcher in 2011 and recently hit her 10-year mark as a staff scientist. She plans to use the DOE funding to make fundamental measurements of current flow in a dense plasma focus Z-pinch that "will help us understand and improve the device." She intends to carry out the work alongside postdocs and other staff members.

Xue Zheng, a research scientist in the Atmospheric, Earth, and Energy Division in the Physical and Life Sciences Directorate, was nominated in the Office of Biological and Environmental Research category for her work in aerosol-cloud processes in which she analyzes atmospheric observations and climate models to advance the understanding of cloud response to aerosols over ocean and land.



"I feel earnestly grateful to win the award," Zheng said. "I've been inspired by previous award winners' research in my area since I started my postdoc in the Lab. It is a tremendous honor for me to receive this award."

Aerosol particles in the atmosphere can affect the Earth's climate directly by scattering or absorbing radiation or indirectly by changing the properties of clouds (such as cloud particle size or cloud lifetime). This "aerosol indirect effect" on liquid-phase clouds remains highly uncertain in present and future climate scenarios. Zheng's project uses DOE's long-term Atmospheric Radiation Measurement (ARM) observations, complemented by satellite retrievals and numerical simulations, to study the aerosol indirect effect on liquid-phase clouds.

Zheng joined the Laboratory in 2014 as a postdoctoral researcher. Her research area focuses on cloud parameterizations in climate models with her primary interest in boundary layer cloud processes and aerosol cloud interactions. The additional funding will allow her to implement advanced statistical techniques to better detect the aerosol–cloud interactions in DOE ARM observations and DOE Energy Exascale Earth System Model (E3SM).

NIF researchers stood at the threshold of fusion ignition after achieving a yield of more than 1.3 megajoules (MJ), a 25X increase over NIF's 2018 record yield. Credit: John Jet

Lawrence Livermore National Laboratory Director Bruce Tarter, Secretary of Energy Federico Pena, and Congresswoman Ellen Tauscher participated in the groundbreaking on May 29, 1997.

Research Spotlight

NIF experiment puts researchers at the threshold of fusion ignition

The National Ignition Facility (NIF), located at LLNL, is the world's largest and highest-energy laser. NIF's 192 powerful laser beams, housed in a 10-story building the size of 3 football fields, can deliver more than 2 million joules of ultraviolet laser energy in billionth-of-a-second pulses onto a target about the size of a pencil eraser.

NIF enables scientists to create extreme states of matter, including temperatures of 100 million degrees and pressures that exceed 100 billion times Earth's atmosphere. Experiments conducted on NIF make significant contributions to national and global security, could help pave the way to practical fusion energy, and further the nation's leadership in basic science and technology and economic competitiveness. Ignition experiments at NIF are advancing the science toward the eventual use of fusion as a safe, clean, and virtually unlimited energy source.

A Milestone in Laser Fusion

On Aug. 8, 2021, an experiment at NIF made a significant step toward ignition, achieving a yield of more than 1.3 megajoules (MJ). This advancement puts researchers at the threshold of fusion ignition, an important goal of the NIF, and opens access to a new experimental regime.

The experiment was enabled by focusing laser light from NIF onto a target that produces a hot-spot the diameter of a human hair, generating more than 10 quadrillion watts of fusion power for 100 trillionths of a second.

"These extraordinary results from NIF advance the science that NNSA depends on to modernize our nuclear weapons and production as well as open new avenues of research," said Jill Hruby, DOE under secretary for Nuclear Security and NNSA administrator.

The central mission of NIF is to provide experimental insight and data for NNSA's science-based Stockpile Stewardship Program. Experiments in pursuit of fusion ignition are an important part of this effort. They provide data in an important experimental regime that is extremely difficult to access, furthering our understanding of the fundamental processes of fusion ignition and burn and enhancing our simulation tools to support stockpile stewardship. Fusion ignition is also an important gateway to enable access to high fusion yields in the future.

"This result is a historic step forward for inertial confinement fusion research, opening a fundamentally new regime for exploration and the advancement of our critical national security missions. It is also a testament to the innovation, ingenuity, commitment, and grit of this team and the many researchers in this field over the decades who have steadfastly pursued this goal," said LLNL Director Kim Budil. "For me it demonstrates one of the most important roles of the national labs—our relentless commitment to tackling the biggest and most important scientific grand challenges and finding solutions where others might be dissuaded by the obstacles."

NIF Timeline

MAY 1997

NIF groundbreaking ceremony

JUN 1999

Target Chamber installed

OCT 2001

First laser light created

MAY 2003

NIF produces 10.4 kJ of ultraviolet light in a single laser beam, setting a world record for laser performance

MAR 2009

Formal certification of NIF Project completion by the National Nuclear Security Administration

SUMMER 2009

192-beam experimental shots to Target Chamber center begin

JUL 2012

More than 1.8 MJ of ultraviolet energy and 500 trillion watts of peak power delivered to Target Chamber center

SEP 2013

NIF implosion yields more energy than the energy absorbed by the fuel, a key step on the path to ignition

JAN 2014

NIF experiment produces 27 kJ of fusion energy; more than half of the yield is attributed to alpha heating A

AUG 2017

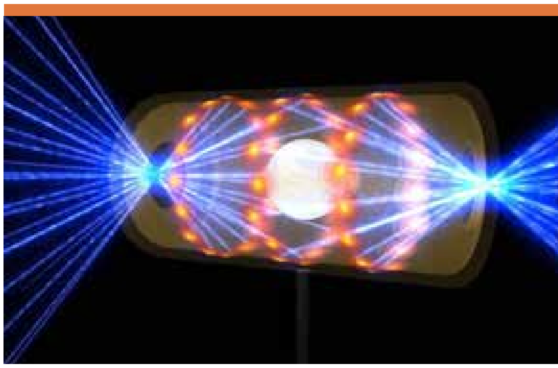
An experiment produces 54 kJ of energy, the highest yield to date

MAY 2018

The NIF lasers set a new energy record, firing 2.15 MJ of energy into the Target Chamber

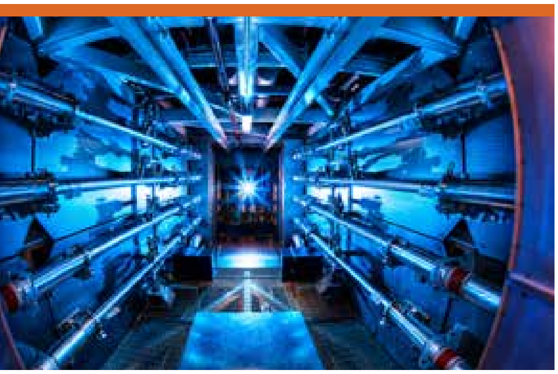
AUG 2021

An experiment achieved a 1.35 MJ of fusion energy output, more than 25 times the record yield set in 2018, advancing NIF to the threshold of ignition

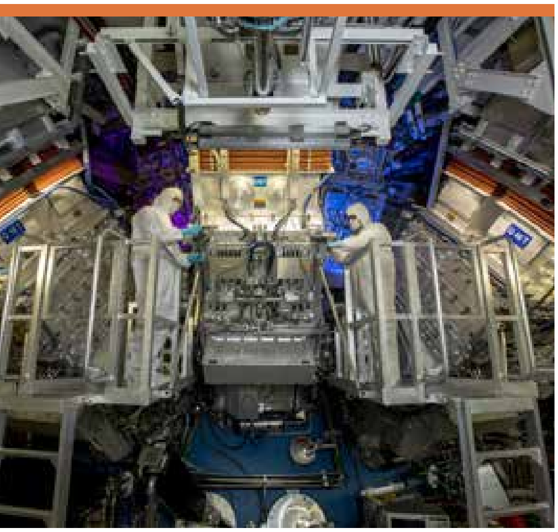


This artist's rendering shows a NIF target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. Ignition experiments on NIF are the result of more than 50 years of inertial confinement fusion research and development, opening the door to exploration of previously inaccessible physical regimes.

Shot-time image from the NIF Target Chamber of an x-ray source creating a plasma wind on system-generated electromagnetic pulse (SGEMP) test objects. The SGEMP campaign, led by Sandia National Laboratories and the U.K.'s Atomic Weapons Establishment, is part of NIF's National Security Applications mission; its goal is to help validate simulation codes designed to determine the effects of SGEMP on various materials.



A color-enhanced image of the inside of a NIF preamplifier support structure. Credit: Damien Jemison.



NIF Target Area operators inspect a final optics assembly (FOA) during a routine maintenance period. Each FOA contains four integrated optics modules that incorporate beam conditioning, frequency conversion, focusing, diagnostic sampling, and debris shielding capabilities into a single compact assembly. A three-week NIF Facility Maintenance and Reconfiguration (FM&R) period began on August 3, with a total of more than 235 tasks completed before target experiments resumed on August 26. Credit: Jason Laurea

Collaboration, Dedication, Appreciation

The experiment built on several advances gained from insights developed over the last several years by the NIF team including new diagnostics; target fabrication improvements in the hohlraum, capsule shell and fill tube; improved laser precision; and design changes to increase the energy coupled to the implosion and the compression of the implosion.

Many of those insights and innovations were transformed into solutions through funding provided by LDRD programs at NNSA laboratories. LDRD investments in this foundational work over the last two decades spanned key science and technology areas, including target fabrication, diagnostic tools, and laser-plasma interactions.

One key area of innovation involves a broad range of LDRD-funded work related to the design and fabrication of the targets used in NIF experiments. NIF targets consist of fuel capsules suspended inside hollow metal cylinders called hohlraums. Since target design plays a major role in the success of fusion experiments, the targets are fabricated to meet precise specifications for each experiment, including the capsule's material composition, density profiles, spherical shape, and surface finish.

Over the last decade, LDRD-funded work related to target design and fabrication included a focus on developing novel materials and nanoscale fabrication techniques to assemble structures measuring less than 100 nanometers and being able to manipulate the material to carefully control the thickness of the target's layers. For example, an LDRD project at LLNL made it possible to fabricate high-density carbon material with unprecedented precision for use as the fuel capsule's shell, known as the ablator. These innovative techniques were used for the target fabrication in the high-yield NIF experiment on Aug. 8, 2021.

LDRD-funded research teams continue to explore other innovative target designs. Their work includes development of novel hohlraum shapes, advanced ignition target designs, and capsule designs optimized for symmetric implosions with higher capsule-absorbed energy. These projects lay the groundwork for future NNSA pathways to even higher neutron yields. Additionally, LDRD-funded research allowed scientists and engineers across the country to capture images of the Aug. 8 NIF experiment through their work on integrated circuits, imaging technology, microelectronics, and radiation.

"This significant advance was only made possible by the sustained support, dedication and hard work of a very large team over many decades, including those who have supported the effort at LLNL, industry, and academic partners and our collaborators at Los Alamos National Laboratory and Sandia National Laboratories, the University of Rochester's Laboratory for Laser Energetics and General Atomics," said Mark Herrmann, LLNL's deputy program director for Fundamental Weapons Physics.Looking ahead, access to this new experimental regime will inspire new avenues for research and provide the opportunity to benchmark modeling used to understand the proximity to ignition. Plans for repeat experiments are well underway as researchers take additional shots at producing more fusion energy than the laser energy needed to start the reaction. In the coming months, LLNL scientists will use precisely manufactured equipment to closely observe the hydrodynamics of the implosion and take further steps towards ignition.

National Nuclear Security Administration

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