Los Alamos Science and Technology Magazine | March 2018

1663

Zika risk in the United States

Metamaterial magic

A scientist who digs microbes

Rethinking turbulence

75 Los Alamos
NATIONAL LABORATORY
EST. 1943

Light micrograph of an unnamed soil fungus. The yellow particles are reproductive spores. Millions of unknown bacteria and fungi live in soils, but few have been fully characterized by scientists. Microbiologist Cheryl Kuske has dedicated her career to finding these elusive organisms and understanding their lifestyles—what they eat, what they excrete, and how they interact with other microorganisms and plants. By doing so, she has begun to elucidate their role in the global ecosystem. To learn more, see "In Their Own Words" on page 6.

1663

LOS ALAMOS SCIENCE AND
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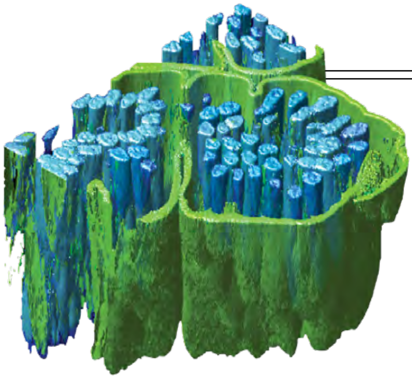
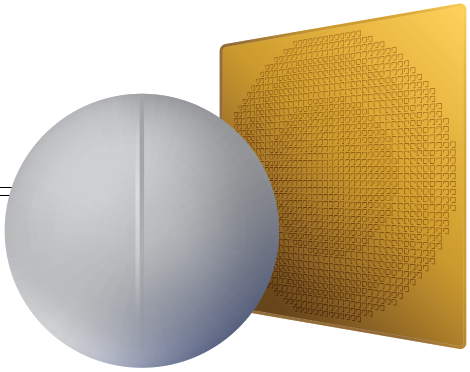
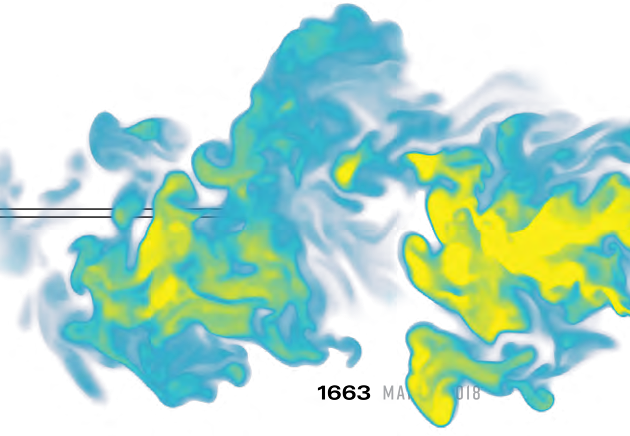


CREDIT: Michael Pierce/LANL



CREDIT: Jim Stein



ABOUT THE COVER

The Volcán de Colima is a 12,500-foot volcano on the border between the Mexican states of Colima and Jalisco. It is one of the most active volcanoes in North America, and when it erupts, it usually does so explosively, earning it the alternate name Volcán de Fuego (volcano of fire). As captured in this exceptionally well-timed photograph, lightning often accompanies this type of volcanic eruption and can in fact be an early indicator that eruption is imminent. The use of lightning as a monitor for volcanic activity is just one of several flashy lightning-related research projects at Los Alamos National Laboratory.
CREDIT: César Cantú

ABOUT OUR NAME

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

ABOUT THE LDRD LOGO

Laboratory Directed Research and Development (LDRD) is a competitive internal program by which Los Alamos National Laboratory is authorized by Congress to invest in research and development that is both highly innovative and vital to national interests. Whenever *1663* reports on research that received support from LDRD, this logo appears at the end of the article.

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Craig Tyler Editor-in-Chief
Eleanor Hutterer Science Editor
Rebecca McDonald Science Writer
Dan Judge Designer
Michael Pierce Photographer
Leslie Sandoval Design Consultant
Denise Sessions Copyeditor
Andrea Maestas Copyeditor

SPOTLIGHTS

Dark Matter Gets a Little Darker

In the 1970s, astronomers realized that galaxies are filled with dark matter: matter that doesn't emit, absorb, or block light (like stars, gas, or dust) but still exerts a gravitational force, as measured by the orbital speeds of stars and other objects circling around the centers of galaxies. For a typical galaxy like our own Milky Way, there is about ten times more dark matter than all the "regular" forms of matter combined.

Four decades of intensive scrutiny later, the dark matter, undeniably present, still hasn't been identified. The leading contender for what might comprise it, or at least most of it, is a yet-to-be-identified elementary particle that swarms invisibly in tremendous numbers throughout galaxies and other astronomical structures. These particles could be passing unhindered through our planet right now, gliding easily through the empty spaces inside atoms, despite having enough mass to generate a powerful collective gravitational pull.

Such a weakly interacting massive particle (WIMP) could account for the majority of dark matter (with comparatively little dark matter in the form of chunkier things like black holes and very dim stars). But if a WIMP can pass clean through the earth, then it can also pass clean through the specialized machines that earthlings build to detect it. Nonetheless, a number of dark matter detectors have been built, running for years on end and accumulating enough non-detections to rule out various categories of WIMPs and other dark matter candidates. Key among the categories that remain are particles somewhat heavier than conventional WIMP candidates; these could be detectable by an unconventional detector.

Astrophysicist Andrea Albert analyzes data from the High-Altitude Water Cherenkov Gamma-ray Observatory (HAWC), a novel Los Alamos-led gamma-ray and cosmic-ray telescope (see "Celestial Mystery Machine" in the May 2015 issue of *1663*). Perched on the slope of a volcano in Mexico, the third-highest peak in North America, HAWC is not a system of lenses and mirrors but a collection of ultrapure water tanks wired up with ultrasensitive light detectors. Whenever a very-high-energy particle from space collides with an air molecule overhead, a spray of subatomic particles rains downward and generates a faint flash of blue light in HAWC's water tanks. It just so happens that—in theory, at least—WIMPs that collide with one another or decay should produce very-high-energy gamma rays capable of triggering this event.

"HAWC was not designed solely to look for dark matter," Albert says, "but it is extremely well suited for picking up gamma-ray signals from higher-mass dark matter particles." Unlike conventional astronomical observatories, HAWC is almost always on, day and night. And it doesn't need to be pointed at any single astronomical object, but rather takes in many targets at once as it consistently sweeps across two-thirds of the sky over the course of the earth's daily rotation. In addition, it is the only instrument in

UGC 12591 is the fastest spinning spiral galaxy known, with stars orbiting the center about twice as fast as in the Milky Way. Stellar orbital speeds—in this galaxy and pretty much every other—are too fast; without additional gravity from a great deal of unseen dark matter, galaxies shouldn't be able to keep their stars from simply flying away.

CREDIT: NASA, ESA, Hubble

operation that probes for dark matter particles beyond a particular mass threshold, about 20,000 times the mass of a proton.

So, has HAWC spotted any dark matter? Well, no, it did what every other detector has done for decades: it ruled out some types of dark matter based on what it didn't see. But strangely, HAWC's strongest constraints on dark matter come from gamma rays it didn't see from a galaxy that didn't exist, as far as anyone knew.

"We looked for gamma-ray dark-matter signals from a number of astronomical sources, including our neighbor the Andromeda Galaxy," Albert says. "The most constraining results came from observations of dwarf galaxies, and our strongest result came from Triangulum II, a dwarf galaxy so faint that it hadn't even been discovered until after we pooled our dwarf-galaxy data. Luckily, because of HAWC's wide field of view and nearly 100 percent up time, we already had data on it."

Dwarf galaxies are what they sound like, typically with only a few hundreds of millions of stars, as contrasted with a full-fledged galaxy like the Milky Way, with stars numbering in the hundreds of billions. Triangulum II appears to contain only about a thousand. They are gravitationally bound together by an unprecedented excess of dark matter, with thousands of times more of it than normal matter. This is a double virtue for Triangulum II and dwarf galaxies in general: more dark matter to collide or decay, producing gamma rays, and fewer normal-matter sources, such as supernovae, to produce gamma rays of their own.

In all, Albert and colleagues examined 15 nearby dwarf galaxies and found no gamma rays that could be attributed to dark matter. But as any dark-matter hunter knows by now, the search doesn't stop there. Over time, more gamma-ray data will be collected from these regions, and, with enough patience, a faint signal may eventually emerge. For now, however, there is only the slow march of determined science, a rigorous and gradual chipping-away process, producing ever-tighter limits on the properties that dark matter could possibly have. In the upper-mass range, it can only have *x* propensity to collide or *y* rate of decay.

"Sometimes in science you have to accept a process of elimination," Albert says. "If we have to, we'll find out what dark matter is by crossing off every single thing that it isn't." LDRD

—*Craig Tyler*

Capturing Life in Motion

Following the inventions of microscopes and x-ray machines, constant technological advances have propelled humans' ability to understand what is going on inside living organisms. But aside from an invasive endoscopic procedure, most methods of visualizing organs or cells produce only one- or two-dimensional still images, leaving much to be desired. For instance, to look at proteins and other cellular components, one must break open a cell and affix the proteins to a microscope slide or suspend them in a gel. To actually see how a protein moves around and functions with other cellular structures, scientists would instead need some kind of molecular video camera.

Over the last several years, many teams have been trying to invent one: developing new microscopes in an effort to capture the three-dimensional movements of particles inside live cells. In 2008, a Los Alamos team led by biophysicist Jim Werner developed an award-winning 3D-tracking microscope, one of only a few of its kind. Today, the scientists are still improving the technology, adding layers of data capture to help them truly understand molecular machinery at work. And with each advancement, they are getting closer to capturing the motion of life at a cellular level. Understanding such interactions and movements has a variety of potential applications, including medical ones, such as testing therapeutics.

The Los Alamos 3D-tracking microscope is based on the design of a typical confocal microscope, which uses a pinhole combined with an objective lens on either side of the specimen in an effort to increase resolution and eliminate out-of-focus light. By making the specimen glow and adding multiple detectors, the scientists can determine the 3D movement. The result is akin to the difference between just looking at an assembled car engine and actually watching the engine run. Instead of simply using microscopy to identify the presence and shape of cellular components, scientists are able to glean valuable spatial information about molecular interactions and overall function.

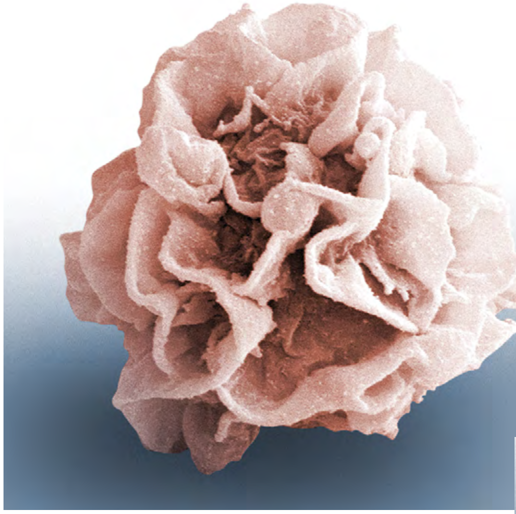
Werner explains that the molecule being tracked is fluorescently labeled (with a green fluorescent protein-type tag or a quantum dot) and positioned in the center of the probe volume so that the light it emits can be captured equally by four photodiode detectors. The detectors are arranged in a tetrahedron shape around the center of the sample in order to analyze the motion along multiple axes. As the labeled molecule moves away from the center, its distance from each detector becomes unequal and, using an algorithm, the team can estimate the new location of the molecule. Next, using the estimate of its current location, the scientists try to move the apparatus to re-center the molecule in the optical probe volume, and repeat the process approximately 200 times per second until they lose the object being tracked.

Using this microscope, Werner and his colleagues can track nanometer-sized (nm) particles at micrometer-per-second velocities (billionth and millionth of a meter, respectively) with a spatial accuracy that depends upon integration time (approximately 100 nanometers accuracy for a 3D position calculated from 5 milliseconds of data) for each of the *x*, *y*, and *z* axes. Along with various collaborators, the team has been able to observe many biological phenomena that could not otherwise be captured. For instance, by tracking the movements of quantum dots in a live cell, the team observed immune-system receptors in action as they initiated a cascade of signaling molecules. In a separate study, the scientists were able to depict the ruffled surface of a mast cell, a key player in allergies and anaphylaxis.

In recent experiments, the team added a specialized spinning disk with thousands of pinholes to the microscope to enable the capture of a still image of the whole cellular environment. This additional image provides an accurate location for where in the cell the tracked molecule's motion is taking place, such as the approach of a protein to a receptor on a membrane. More recently, the team is expanding 3D tracking to new areas, including using the system for time-resolved super-resolution imaging and for studying other important 3D-transport problems outside of the biological sphere, such as how sand-like materials called proppants flow in 3D fracture networks important in hydraulic fracking. But for Werner, biological science and medical applications provide plenty of important targets for study.

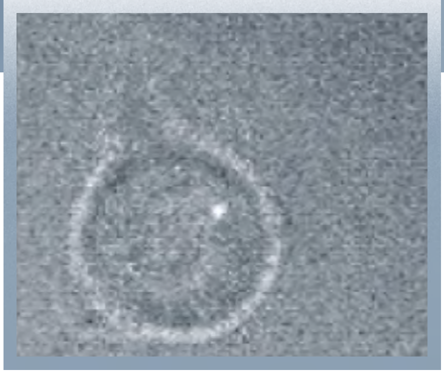
"Understanding how, when, and why individual proteins interact in live cells is critical to understanding and predicting cell response, including when or why a cell becomes diseased, develops cancer, or dies due to exposure to infectious disease," says Werner. "Furthermore, the insight about how proteins interact with cell membranes could potentially help us test the efficacy of getting therapeutic drugs into cells." With innovative microscopy such as his 3D-tracking microscope, this understanding might be more attainable than ever before. LDRD

—Rebecca McDonald

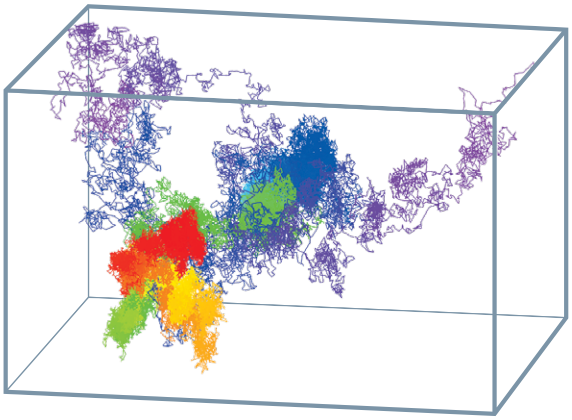


The components of living cells often have complex, even variable shapes that are critical to their functions. This mast cell is part of the immune systems of vertebrate animals. When stimulated, its surface becomes highly irregular and ruffled, a characteristic that is difficult to discern with many microscopy techniques.

CREDIT: Bryan Kaehr/Sandia National Laboratories; Cell silica composites. Bryan Kaehr, et al. PNAS Oct 2012, 109 (43) 17336-17341.



(Above) A 2D white-light image of a quantum dot being tracked inside a mast cell. The image gives context to the location of the quantum dot, but does not show the intricacies of the cell's unusual surface. (Below) Data taken from Los Alamos's 3D-tracking microscope while tracking a quantum dot in a mast cell. The data indicate motion in three dimensions for a duration of six minutes (the color change across the rainbow corresponds to this passage of time). The complex trajectory sheds light on the unusual shape of a stimulated mast cell.



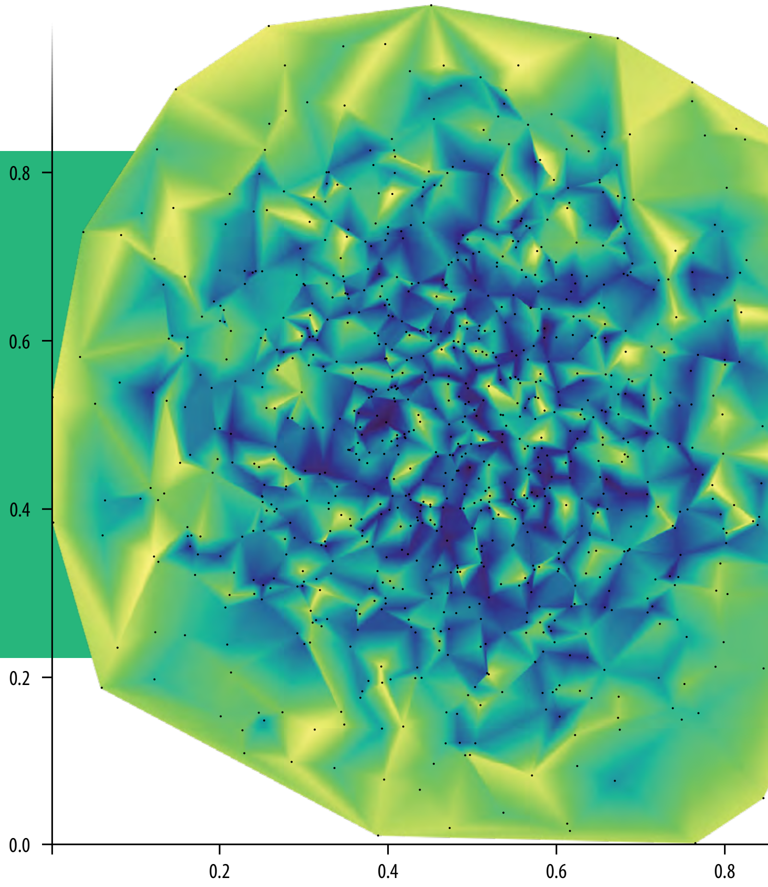
Better Data Just Can't Wait

Imagine this: You're a scientist with time scheduled on a high-end user facility, such as a powerful x-ray source, particle accelerator, or observatory. You wrote a proposal to use the facility, were one of the fortunate 10 or 20 percent to receive approval, obtained funding, and showed up for your 72-hour time slot. You successfully crammed in all your experiments—working night and day with brief naps and take-out meals—and returned home with a massive amount of new data.

Now imagine this: Half a year later, you're still chugging through the terabytes of experimental data, and you make an unexpected discovery. Maybe it was a faulty measurement or some incorrect setting when you conducted the experiment. Or maybe it's something groundbreaking, something you hadn't planned to look for that just barely showed up in a small subset of the data. Either way, here you are, your time on the fancy user facility long gone, and only *now* do you see what you really *should have* measured while you were there. Only now do you see that the tsunami of data you did collect has errors or is in some other way less valuable than it could have been.

It's not such a rare occurrence. Much of modern science is so complex that it requires time-consuming supercomputer simulations to interpret the effects of adjusting experimental parameters and equally time-consuming data reduction to interpret the results. Furthermore, as experimental facilities have grown more sophisticated in their instrumentation and data collection, the volume of data they produce has grown to the point where it takes months or even years to pore through it and see what it really contains. And by then, it may be too late.

That's why Laboratory computer scientist James Ahrens, experimental materials scientists Cindy Bolme and Richard Sandberg, statistician Earl Lawrence, and a team of other scientists of various disciplines started the ASSIST project. Short for Advanced Simulation, experiments, Statistics, and Information Science and Technology, ASSIST defines a software workflow that allows scientists to compare simulation results with experimental data as the data is generated and presents the results in a ready-to-interpret visual format. This enables scientists to make key decisions on the fly about what to measure next—that is, what experiments are most worth doing in the limited time available.



ASSIST data visualization comparing two input parameter values, one on each axis (for example, the temperature at which an experiment is being conducted and the intensity of a laser being used), with the color scale representing uncertainty in current knowledge. The *x* and *y* coordinates of the most uncertain regions (yellow) indicate the experimental-parameter settings that would reveal the greatest amount of new information.

ASSIST accomplishes this with an emulator, a fast statistical model that replicates a more computationally expensive simulator. Using previously obtained simulation results for different combinations of input parameters, the emulator is trained to predict variations in what the full simulation would produce with different inputs. ASSIST quickly extracts only the most relevant measurement data and compares that with the emulator's predicted outcomes. It then employs powerful visualization tools to show the comparison graphically, in various formats, to scientists who might want to change tack as a result. And for experiments intended to seek a desirable set of output values, it can estimate the proper conditions to help the experimenter get there. Critically, the whole process is fast enough to help scientists make decisions during their brief experimental window.

But perhaps ASSIST's greatest strength is its ability to identify exactly where things get interesting and update that assessment with each new data point it receives. It can analyze a large multidimensional input and output space and suggest combinations of parameters to test in order to gain the best information about the least-understood aspects of the system under study. It identifies which combinations of input settings change the outputs the most and which settings are so sensitive that dialing them a hair in either direction means the difference between night and day—right there, right then, for the scientist racing to collect data all night and all day. LDRD

—*Craig Tyler*

Dr. Kuske in one of her microbiology labs. The image on the microscope screen is a photosynthetic cyanobacteria, *Microcoleus vaginatus*, which is a major constituent of biological soil crusts in the arid Southwest.

CREDIT: Michael Pierce/LANL

IN THEIR OWN WORDS

CHERYL KUSKE explains how to better understand the environment by examining its tiniest inhabitants.

SOMETIMES I GET ASKED WHAT IT'S LIKE to be a scientist and have a career in research. I've found the best way to answer this is to share my favorite M.C. Escher drawing, one that I keep framed on the window ledge in my office. The drawing depicts the surface of a person's desk upon which a sketchbook is laid open, surrounded by various accoutrements such as a bottle, a plant, and a book. On the page of the sketchbook, and—in true Escher fashion—there is a melee of abstract shapes from which the form of a reptile emerges on one side, climbing up off the page, walking across the various desk accessories, stopping once to blow steam from its nostrils (Yay! Success!), and then climbing back down into the chaos of shapes on the page.

I have always enjoyed working on complex biological systems where easy answers are rare. The answers I seek require understanding the intricate and elusive interactions of the millions of microorganisms found in soils, sediments, and water. Escher's melee of shapes and future reptile parts represents most of my time spent as a research scientist—swimming in data that doesn't always make sense or have a direction, trying to prove one hypothesis or another (and most of the time disproving it) and then going on to another hypothesis. Sometimes, I find that pieces come together as a cohesive idea or discovery—like the reptile—and it takes me somewhere out of the melee for a while, allowing me to enjoy the success and teaching me something before I go back into the pool of data to start building on what I've just learned. The key to being a scientist is understanding how to recognize a success when you're down in that melee; you have to figure out what information is useful and what is not. Fortunately, through the course of my career as a microbiologist, my incredible team and I have found a few of these "reptiles," and they have taught us a great deal about the tiny microbial world that surrounds us and interacts with our planet and its inhabitants.

Out of the tide pools

Growing up in coastal North Carolina, I was fortunate to spend my early years exploring firsthand the natural world in the estuaries and wetlands near my house. In a canoe with muddy sneakers, I learned about frogs, turtles, water lilies, and algae.

I was and still am in awe of biochemistry, biodiversity, and how plants, fungi, and bacteria live and interact with each other. For instance, studying what an organism metabolizes—what it eats and excretes—gives us clues about its impact on its surroundings, such as cycling carbon or nitrogen. Another example is that as organisms interact with other living things, some of them can cause devastating disease, which we want to know about. Finally, we have also learned that the compounds some bacteria or fungi produce in order to protect themselves from each other can in fact be used by humans as life-saving pharmaceuticals and antibiotics. Today we are discovering more and more evidence about how these microbes impact everything from the balance within our bodies to that of the entire global environment. It's the interactions and the interfaces between participants that hold the keys.

> THE KEY TO BEING A SCIENTIST IS FIGURING OUT WHAT INFORMATION IS USEFUL AND WHAT IS NOT.

A metaphor for the scientific process?

CREDIT: M.C. Escher's "Reptiles" © 2018 The M.C. Escher Company-The Netherlands. All rights reserved. www.mcescher.com

My graduate work and first job were in plant pathology and the biochemistry of plant disease: studying which organisms cause disease in crop plants like rhododendron, soybeans, and tree fruits. I became interested in the study of uncultured bacterial pathogens—bacteria that have not been grown in a laboratory and therefore are not well-studied—being discovered by microscopy and DNA detection. Little did I know that later in my career I would have the molecular tools to thoroughly examine these finicky organisms and their elusive lifestyles without having to isolate and grow them on a Petri dish.

After earning my Ph.D., I came to Los Alamos and began a postdoc in the then Life Sciences Division (now Bioscience Division). My postdoctoral work was to investigate the enzymology of heavy-metal resistance (primarily cadmium) and sequestration in the jimsonweed plant. I also began a project to pioneer new techniques for isolating fragments of DNA directly from soil and aerosol samples to look for "select agent" pathogens and their close genetic relatives that may share common DNA traits. Select agents are specific pathogens that have the potential to pose a severe threat to animals, plants, or the public.

As my career took shape in the mid-1990s, I began to focus on two major aims, supported by different agencies. The first was to document the "background" of microorganisms related to the current suite of select bacterial agents present in the air and soil of major U.S. cities. The second was to identify and track the metabolic responses of soil bacterial and fungal communities to increases in temperature, changes in precipitation patterns, and increases in nitrogen deposition (from industrial agriculture and power plants) in arid grasslands, cyanobacterial biocrusts, and pine forests. Both of these projects have been ongoing for many years and have led to a variety of important discoveries.

One of our Escher "reptiles" for the first aim came when we discovered that for some pathogens, such as *Francisella tularensis* (which causes tularemia, or rabbit fever), many of the pathogen's near relatives that had not previously been identified by culturing, in fact, occur naturally in the environment—particularly in soil or coastal marine areas. Early surveillance schemes did not take into account the natural presence of these close relatives, which could hamper detection scenarios by generating false positives. We have worked on this issue for a couple of decades now and have identified many new *Francisella* species present in the environment, ones that can be pathogens and that are closely related to the select agents. Sequencing and comparing all of these genomes was one of the eureka moments in my career because we could now define specific DNA fragments and begin to understand the purpose of these organisms—such as what roles do they have in the environment (e.g., cycling carbon) or do they cause disease (making it vital to be able to detect them). Although at the time it was conventional to grow pure, isolated cultures of target organisms to sequence their genomes, we were able to develop culture-independent methods of isolating fragments of DNA or RNA that could be amplified and sequenced to identify the organisms in environmental samples.

WE HAVE BEEN EXAMINING HOW CHANGES IN THE ENVIRONMENT IMPACT MICROBIAL COMMUNITIES IN THE SOIL.

Building on the early success of the environmental DNA and select-agent pathogen work, I began to further investigate ways of using DNA-based approaches to identify and characterize other kinds of microorganism communities—including ones that are not pathogenic. Through an environmental study at Sunset Crater near Flagstaff, Arizona, we discovered another one of our "reptiles": a whole new kingdom of bacteria called *Acidobacteria*. This was a great discovery, but the finding raised more questions than it answered. Members of this kingdom are ubiquitous in soils and sediments around the world. They are very diverse and the handful of cultured members that we and others have obtained displays very different lifestyles. We have sequenced many of their genomes; however, we still don't know what they are doing in soils. For example, the most abundant *Acidobacteria* members in the Los Alamos area are highly diverse, and although they are likely stuck to the soles of all of our shoes, they have not been cultured or sequenced and their functions in the ecosystem remain unexplored.

Genomics and sequencing advances

Our DNA-based approach was proving to be a good technique, but the timing of it all—in the mid-2000s—coincided with extensive advances in genomic sequencing that would lead us to even more breakthroughs in soil ecology. Sequencing machines became more automated, making the process exponentially less expensive and much faster, but often resulting in more data than we knew what to do with. Fortunately, cutting-edge bioinformatics tools help scientists like me sort through this "big data" to make sense of it all by comparing new sequences with validated ones and helping us recognize relationships among organisms and their traits.

The most significant part of this advancement for my research purposes was that we could now sequence an entire microbial community together, as one complex sample. By sequencing all the DNA in a community at once, a process called metagenomics, we can learn about all the types of organisms present and therefore the potential metabolic activities of the community as a whole. Alternately, a related process called meta-transcriptomics is a way to understand what genes are currently being used in the community by sequencing the actively transcribed messenger RNA in the sample. (Messenger RNA molecules are only made when a cell needs to produce a certain protein or enzyme for a specific function.)

The tools had arrived. These advances in genomics improved our ability to identify the composition of microbial populations—which microbes live in which environments—as well as what roles they have in different ecosystems. We anticipate this work will continue to give rise to a better

Samples from a soil microcosm experiment. Soils from an eastern pine forest (darker soil) and Utah grassland (lighter soil) are incubated in sealed bottles and exposed to various environmental conditions. For example, some are inoculated with target fungal and bacterial communities and then assessed over time for carbon dioxide production, dissolved organic carbon, and the organismal makeup of the community.

understanding of the complex interactions between microorganisms. The relationships within these soil communities are the "reptiles," and little that is useful will come from examining them in isolation.

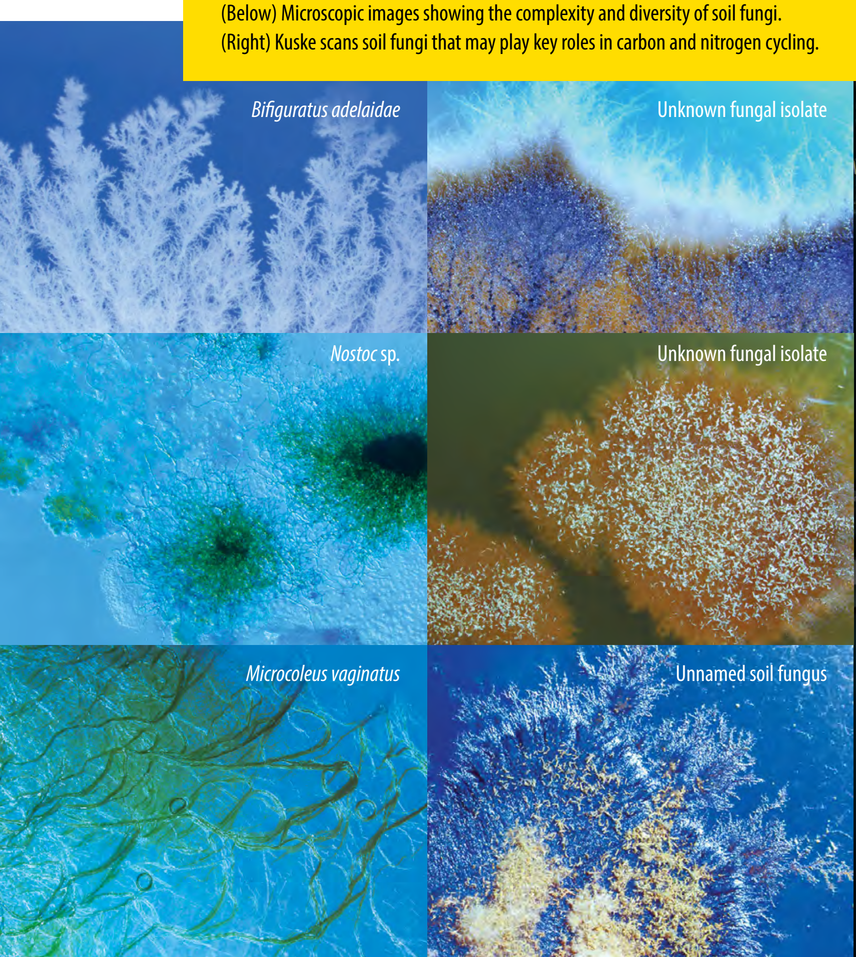
Relationships matter

So now I get to spend my time truly investigating interactions in the microbial world: the thing that inspired me long ago. One of the dominant interactions among soil microorganisms is to decompose organic matter and recycle nutrients in the ecosystem. Dead plants and animals are deposited in the ground, and as the fungal and bacterial communities break down their tissues, their components are recycled into other living things. Soil fungi are experts at this. Some nitrogen and carbon atoms go back into the soil to feed new plant growth, while others are released into the atmosphere in the form of carbon dioxide or nitrogen gas. This nitrogen and carbon cycling is critical to achieving balance in our global ecosystem.

In 2007, I secured long-term funding for a Department of Energy "Science Focus Area (SFA)" in Soil Metagenomics and Carbon Cycling in Terrestrial Ecosystems. Through this program, my team has been able to examine how changes in the environment impact microbial communities in the soil in arid grasslands and pine forests, as well as how examining these changes can help us model what the environment might be like in the future. For instance, as the modern, industrial world releases more carbon and nitrogen into the air and the soil, we want to understand what is happening to the microbial communities. Are they feeding more carbon and nitrogen back into the air where it can exacerbate warming? Or are they sequestering this new biomass in the soil? Furthermore, we need to ask how these populations respond to increases in air temperature or changes in the pattern and timing of regional precipitation.

To do this work, we set up various types of experiments, all involving the collection of soil samples for metagenomic sequencing and analysis. For the first phase of our project, we collected samples from DOE sites called Free Air Carbon Dioxide Enrichment (FACE) field experiments. These sites were replicated free-standing enclosures, placed in multiple biomes across the United States, where carbon dioxide was pumped into sectioned-off areas of vegetation for a sustained, long period of time, usually many years. By 2012, our team was able to draw a number of conclusions about the soil microbes and how the elevated carbon dioxide affected them. For instance, we observed that elevated carbon dioxide impacts were identifiable but were often strongly influenced by other local variables like soil depth or plant type. We also learned that decomposition is due to the interplay of the fungal and bacterial communities, each having hundreds to thousands of species in a single gram of soil. This is indeed a complex system. The fungal and bacterial communities are structured based on different soil features, and we were surprised to find a much broader taxonomy of nitrogen-fixing bacteria than expected.

(Below) Microscopic images showing the complexity and diversity of soil fungi.
(Right) Kuske scans soil fungi that may play key roles in carbon and nitrogen cycling.



CREDIT: Michael Pierce/LANL

For the second phase of our project we collected soil from temperate ecosystems in the pine forests of North Carolina and in the arid grasslands of Utah. We also refined our genomics strategy—based on our experience in the first phase—and decided to do much more meta-transcriptomics so that we could really identify the metabolic activities relating to changes in temperature, precipitation, and nitrogen deposition that are dominant in each ecosystem.

By sequencing and analyzing the mRNA in soils, we have begun to pinpoint which specific enzymes are responsible for impacting the fate of carbon in the soil. For instance, some microbial processes use enzymes that will create dissolved organic carbon (DOC) as a byproduct, while other processes and enzymes will create carbon dioxide. DOC will ultimately remain in the soil and likely be incorporated into new plant material, while carbon dioxide could end up back in the atmosphere. When we sequence mRNA, we can identify statistical information about the prevalence of each enzyme under different treatment conditions, giving us an idea of the overall carbon balance in a specific area of soil.

> THE LAB HAS FACILITATED STUDIES I WOULD NEVER HAVE DREAMED OF DOING AT A UNIVERSITY.

Another way my team is examining the terrestrial world is to create test systems in the laboratory. Here we are taking samples from the abovementioned sites and creating microcosms in the laboratory, so we can artificially alter the conditions in a controlled environment, such as by adding nitrogen or water to the soil. By comparing transcriptomic data from the microcosms with those from the field, we can begin to identify trends that we hope will help us model future outcomes, such as: Will an increase of certain microbial species translate into an increase of carbon dioxide released back into the atmosphere? Which are the more important contributors to this process, fungi or bacteria? And how can we manage these populations to track or manage carbon sequestration in soils?

Through this research, our team hopes not only to provide better input variables for process models of what the terrestrial environment will be like in the future, but also perhaps to help mitigate the impacts of excess carbon. For instance, by identifying the types of microbes that contribute to keeping carbon in the soil (such as those that produce DOC), we are investigating the idea of "inoculating" or seeding soil with the right mix of microbes to alter the carbon flow towards increased sequestration.

Over the years, we have emerged from the Escher-sheet to make some striking discoveries. We have found that the environment is not a clean slate upon which we detect pathogens but instead harbors a complex microbiome that is required for elemental cycling and response to environmental changes—and most of this microbiome remains uncultured and is therefore inaccessible except by DNA- or RNA-based surveys. We have also observed that the surface soils in forests and grasslands are highly stratified and contribute significantly to carbon and nitrogen cycling. The soil fungal and bacterial communities are intimately associated with almost all plant life where, through root interactions, they control plant growth, survival, and resistance to pathogens. Although unseen by the naked eye, these organisms control many functions in terrestrial ecosystems.

It's not just the reptiles

I remember the moment I realized I wanted to be a scientist. I was in a horticultural science class as an undergraduate, hearing a woman speak about a career in research. At that moment, I realized that's what I wanted to do—it seemed like a career that had no rules. I've since amended this impression, based on my experience, and one of the rules I've learned is that you have to get out of the Escher melee as much as possible. I tell my students to think outside the box and to be brave enough to discuss ideas with others from different scientific backgrounds because their perspective can help you find answers. I also tell them to take advantage of the diversity of their colleagues, hone their communication skills, and find common dialog with others to discuss their science. Finally, I recommend they have fun in research by looking for novel hypotheses and unusual phenomena, but also that they be ready to drop a topic and explore a new one every year.

Coming to New Mexico from North Carolina, I found Los Alamos to be an unplanned surprise. I knew little about the Manhattan Project or the history of World War II, and I wasn't sure I would fit in well. But it has been an enormously rewarding and successful adventure. Every year that I'm here I learn more about other scientific disciplines, such as physics, engineering, chemistry, and especially computation. This diversity enables us scientists the flexibility to craft a research team appropriate for each scientific grant, and being at the Lab has facilitated studies I could never have dreamed of doing at a university and could not have done as a solo investigator. Los Alamos has exceptional scientific, technical, and support staff all in one place. By working in this complex, interdisciplinary environment, I have also come to appreciate more about the Lab's history in World War II and the Manhattan Project—how innovation was fueled by allowing scientists of varied backgrounds to come together and push the boundaries of knowledge.

—Cheryl Kuske

DEFINING THE DANGER

How likely is it that the U.S. will experience outbreaks of Zika and chikungunya in the near future?

WHEN IT COMES TO DISEASE OUTBREAKS, all it takes is one. One bad egg, one sick animal, one bloodsucking mosquito, or one infected person; any of these can initiate an outbreak. But the conditions have to be just right, and there are a lot of different variables that go into the conditions being just right. Los Alamos mathematical epidemiologist Carrie Manore and her colleagues use computer models to examine the likelihood that conditions in parts of the United States could soon be just right for outbreaks of the important mosquito-borne viruses Zika and chikungunya.

Zika virus, long known in Africa and named for the Zika forest of Uganda, burst into the mainstream consciousness in 2015, when large outbreaks in South America were associated with severe birth defects in the brains of newborn babies. Shortly thereafter, research also linked the virus to a disorder in adults, called Guillain-Barré syndrome, in which a person's immune system attacks and damages his or her nervous system.

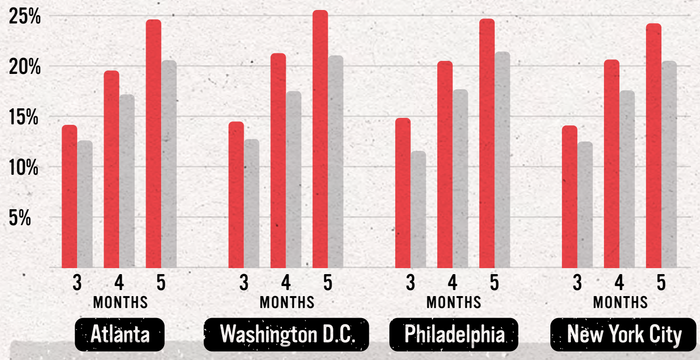
Prior to Zika's overwhelming debut in the Americas, a different virus—chikungunya—had been setting off alarm bells in the disease-surveillance community. Chikungunya virus, named for a Makonde word describing the bodily contortions of its victims, has long been known in both Africa and Asia, where it causes large outbreaks of disease involving severe, sometimes long-term, debilitating joint pain.

The alarm bells that chikungunya virus, and now Zika virus too, are setting off have to do with the mosquitoes that transmit these viruses to humans. The mosquito *Aedes aegypti* is considered the main vector of both Zika and chikungunya in tropical regions, while its close relative *Aedes albopictus* is an important vector in temperate regions. Both of these mosquito species are increasingly being found in larger areas of the United States, and in greater numbers, than ever before. And they are bringing their viruses with them.

Close to home

A female mosquito acquires a virus when she ingests the blood of an infected host, be it human or other animal. The virus replicates prolifically inside the mosquito, eventually reaching the salivary glands. When the mosquito next takes blood from a host animal, saliva that is full of virus gets injected into the animal. The virus now replicates prolifically inside the animal, circulating throughout the blood, so when another mosquito takes some blood, she gets a load of virus too. This is a basic mosquito-borne virus transmission cycle. But every virus-mosquito-host-environment system is different, in terms of epidemiology; not every exposure will lead to infection, and not every infection will result in severe disease. There are a lot of variables that affect whether or not disease will develop in an infected individual, and how easily the infection will be spread to other members of the community.

Based on that understanding, Manore defined the following human populations for her model: susceptible human, exposed human, reported infected human, unreported infected human, and recovered infected human. The model also included



The length of mosquito season strongly predicts the likelihood of an outbreak. Here, the percent of model runs resulting in 100 or more cases of infection are shown for two different viruses (Zika in red, chikungunya in grey) across four major temperate-zone cities. As mosquito season is lengthened from three to five months, the risk of large outbreaks also increases.

similar mosquito populations: susceptible mosquito, exposed mosquito, and infected mosquito. (Recovered people are no longer infectious and are immune to re-infection, but once a mosquito is infected, it is infected and infectious for life.) In addition to defining these populations, Manore also had to quantify how each population relates to the others—for instance, how the number of infected mosquitoes influences the number of exposed humans, and how the number of infected humans influences the number of exposed mosquitoes.

Some of the variables that affect the numbers assigned to each of these parameters include the duration of the active mosquito season, the percentage of mosquitoes that become infected after ingesting the blood of an infected human, the percentage of mosquitoes that bite humans (rather than other animals), and the number of mosquito bites per person, per day.

ALL IT TAKES IS ONE NON-AVERAGE YEAR TO BEAT AN AVERAGE-BASED PREDICTIVE MODEL

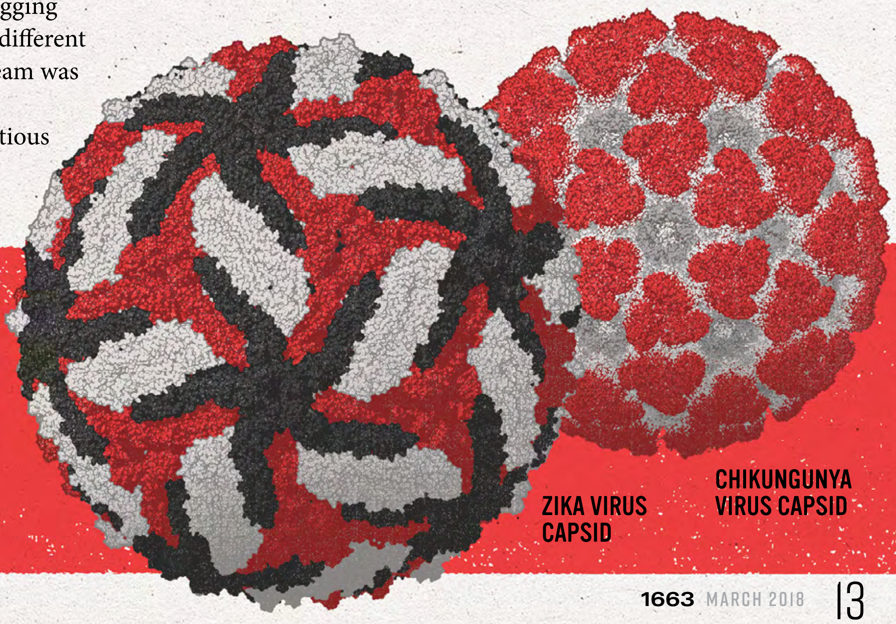
A mathematical model has to be at once usable and informative. "It's really complicated and challenging to strike the right balance between simplicity and complexity," Manore says. "There are humans, mosquitoes, ecology, behavior, physiology, and climate, all interacting, and it's incredible to be able to pick that complex system apart, assign a number to each piece, then put it all together again and see what happens."

Focusing on the numbers for *Aedes albopictus* because it is more relevant to North America than *Aedes aegypti*, Manore and collaborators devised a model that takes into consideration the whole range of numbers for each of these variables and more. The number ranges themselves were gleaned from exhaustively combing the research literature. After plugging them into the model, and testing tens of thousands of different combinations across all relevant number ranges, the team was able to draw some interesting conclusions.

Manore's model revealed that, out of all the infectious travelers who return from abroad to U.S. cities with high human and mosquito densities, like Houston or Miami, 50 percent could initiate an outbreak. While most of the potential transmission events would only spread the virus to one or two more people, the model showed that 10 percent could initiate a sizeable outbreak of 100 or more people. Additionally, although *Aedes albopictus* mosquitoes bite humans less frequently than *Aedes aegypti* mosquitoes do, Manore's model showed that human outbreaks are possible with less than half—just 40 percent—of mosquitoes taking human blood. These numbers represent non-average, yet not-at-all unlikely conditions.

A tempting and more straightforward approach might be to take the average value for each parameter—average length of mosquito season, average number of mosquito bites per person, average time between a mosquito being exposed and becoming infectious, etc.—and just plug those numbers into the model. This would definitely be easier than testing across the full range of possible values for each parameter, but that approach is far too simple, explains Manore.

"Average sampling can lead you astray," she says. "It suggests there is no risk, and we know there is risk because we've already seen actual local transmission in Florida and Texas. Our approach lets us sample the full space of



Although they cause similar disease symptoms (including fever, headache, rash, joint pain, and muscle pain), occur in some of the same regions, and are transmitted by the same mosquito species, Zika virus (left) and chikungunya virus (right) are not closely related. Zika is a flavivirus, belonging to the same family as Yellow Fever, Dengue, and West Nile viruses. Chikungunya virus is a togavirus, belonging to the same family as Rubella virus as well as Eastern-, Western-, and Venezuelan-equine encephalitis viruses.

possibilities and capture all of the non-average but still not unlikely scenarios. The winning combination for us—the set of conditions most likely to result in local transmission—was different from across-the-board averages. All it takes, after all, is one non-average year to beat an average-based predictive model."

The strongest driver of outbreak likelihood in U.S. cities was, perhaps not surprisingly, the mosquito season—specifically its length and warmth. Typically in temperate regions, winter can be relied upon to put an end to mosquito season. Mosquitoes die out when the temperatures get cold, so virus transmission too dies down. But in areas without hard freezes, mosquitoes and their viruses may never fully disappear between one peak season and the next. With annual temperatures creeping steadily up, mosquitoes are primed to inhabit new regions and to enjoy longer active seasons in coming years.

A MODEL BUILT AROUND
REAL OUTBREAKS
OF THE PAST CAN
HELP PREPARE
FOR THE FUTURE

Out of all the combinations of variables tested, those that included longer mosquito season lengths returned higher risks of outbreak. This may seem obvious, but part of the point of modeling is to validate and quantify what would otherwise be mere suspicions. The model also confirmed that the peak of mosquito season was the most likely time for an outbreak to start, compared to either the beginning of mosquito season, when activity is just ramping up, or the end, when it's starting to die down. And with summer being both peak mosquito season and also peak travel season, the likelihood of an infectious traveler returning to a U.S. city during the height of mosquito season seems not too remote.

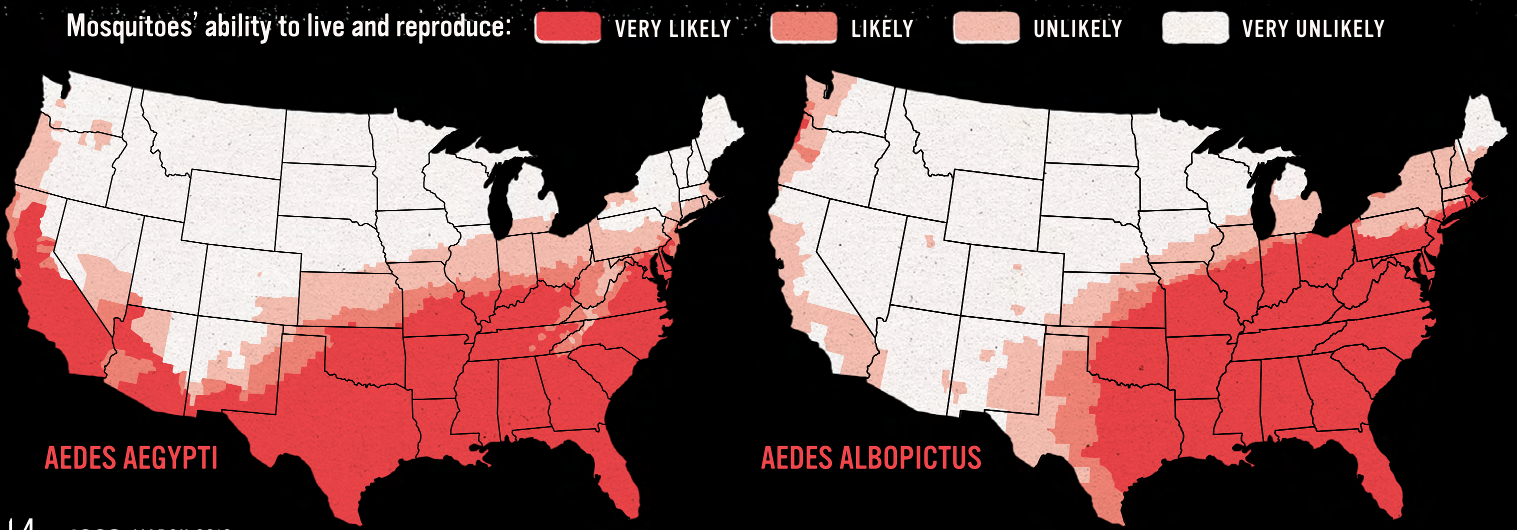
Farther abroad

Some of the places from which infectious travelers return to the United States—like Central and South America—are also of interest to the team. Many countries in these regions, where it never freezes and virus transmission occurs year-round, have seen firsthand the devastating effects these viruses, particularly Zika, can have.

To help the public health entities in these areas develop mitigation strategies and minimize the extent of outbreaks, the team developed a model specific to the Zika outbreaks of 2015 and 2016 in three countries of interest: El Salvador, Colombia, and Suriname. (The choice of countries was motivated in part by availability and consistency of outbreak data.) The idea was that if the scientists could build a model around real outbreaks of the past, that model would tell them what to expect from the future.

The results were mixed. For El Salvador and Suriname, the model performed well, predicting with strong accuracy the extent and timing of the outbreak. For Colombia, however, the model did not perform as well. It turns out that the Colombian outbreak was actually two distinct outbreaks, occurring in partially overlapping space and time. So the model, which was a single-outbreak model, didn't fit well. The team is presently developing additional models to look more closely at Colombia, at a state and city level rather than country level, to try to resolve those outbreaks at a finer spatial scale.

The power of these models lies in the ability to forecast and prepare for future outbreaks. Zika infection most likely has a low reporting rate—either people don't realize they are infected or they don't have the means to report it—so even for outbreaks in the past, public health operations may not know how many cases there really were. Having a way to reliably estimate timing and extent of past outbreaks is critical for



Estimated range of *Aedes aegypti* and *Aedes albopictus* mosquitoes in the United States, 2017. Much of the country is already ecologically able to support populations of two species of mosquitoes that transmit Zika, chikungunya, and other viruses dangerous to humans.

Credit: U.S. Department of Heath and Human Services, Centers for Disease Control and Prevention preparing for the next one: planning vaccination campaigns, bolstering reporting efforts, and anticipating the numbers of birth defects.

In the forecast

This work highlights the need for more data on *Aedes albopictus*—especially density, behavior, and seasonality—to make better forecasts for cities in the temperate United States. One avenue that Manore and others at Los Alamos are pursing is to use high-resolution satellite imagery to identify parcels of land, based on characteristics like wetness and greenness, that may provide a good mosquito habitat. Another tool that has proven useful for other diseases, like influenza, is internet search data. The number of searches for certain disease-related terms for a particular geographic area can be a good indicator of the presence of that disease in that area.

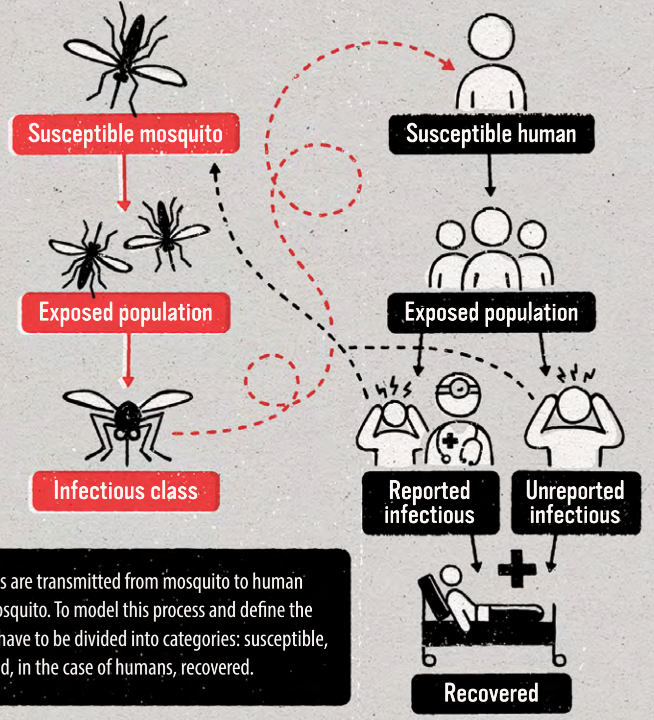
Something Manore plans to keep a close eye on in the immediate future is the effect of last season's major hurricanes: Harvey in Houston, Irma in Florida, and Maria in the Caribbean. After hurricane Katrina hit New Orleans in 2005, the following mosquito season brought a distinct uptick in local transmission of West Nile virus. Will 2018 see similar surges in mosquito-borne disease to the areas devastated by hurricanes in 2017?

People who live in these areas aren't necessarily at the mercy of the mosquitoes—there are common-sense protection measures they should take. Window screens, mosquito repellant, and eliminating sources of standing water go a long way toward reducing risk. So, although these measures were not included in Manore's analyses and may temper future outbreaks, the Los Alamos team achieved its main goal, which was to prove the power of its mathematical approach.

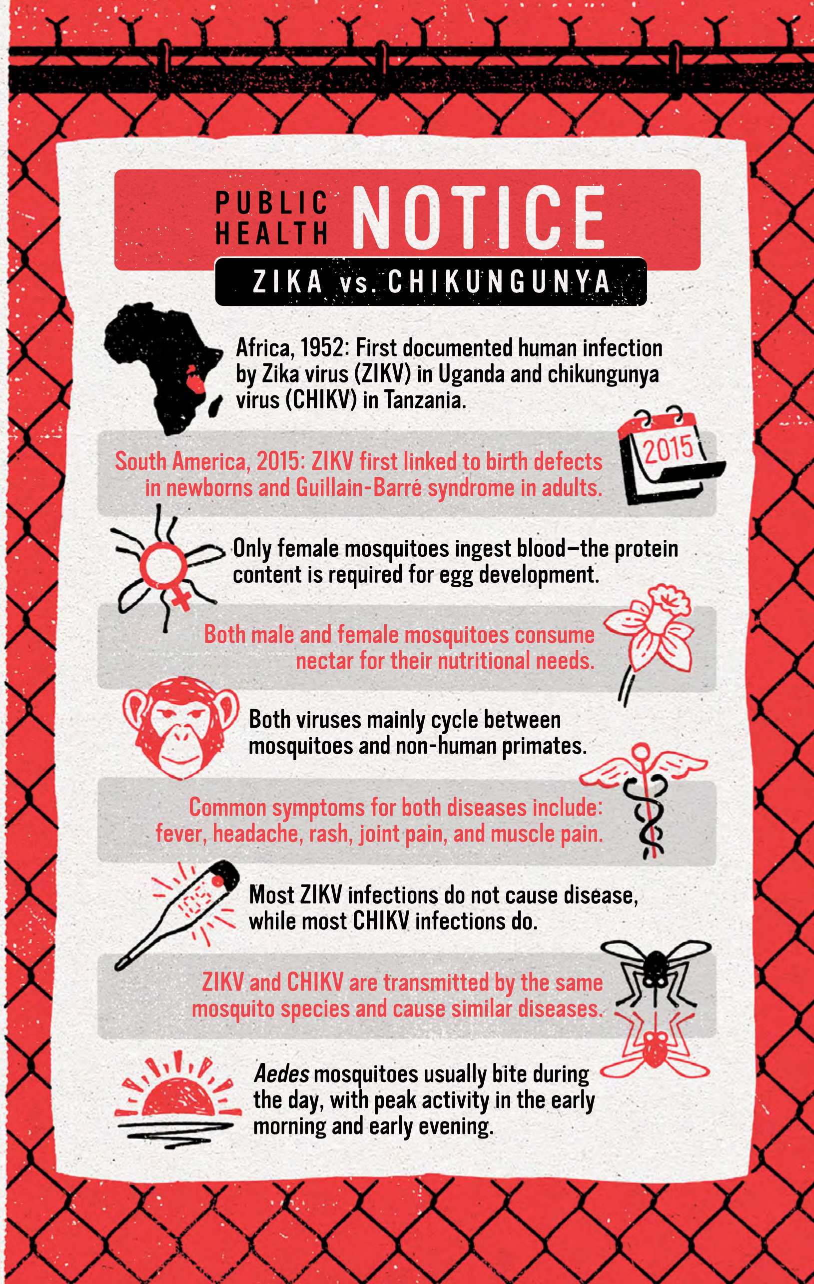
The ability of scientists like Manore to create accurate and timely forecasts for outbreaks of potentially devastating diseases highlights the importance of collaboration across disciplines.

"It's absolutely critical to have a multidisciplinary team," emphasizes Manore. "Biology, ecology, virology, mathematics, remote sensing, computer science, and data analytics all play a part, and they all have a presence here. Los Alamos is one of the only places where this is true." LDRD

—Eleanor Hutterer



Mosquito-borne viruses are transmitted from mosquito to human and from human to mosquito. To model this process and define the risk, both populations have to be divided into categories: susceptible, exposed, infectious, and, in the case of humans, recovered.



PUBLIC HEALTH NOTICE

ZIKA vs. CHIKUNGUNYA

Africa, 1952: First documented human infection by Zika virus (ZIKV) in Uganda and chikungunya virus (CHIKV) in Tanzania.

South America, 2015: ZIKV first linked to birth defects in newborns and Guillain-Barré syndrome in adults.

Only female mosquitoes ingest blood—the protein content is required for egg development.

Both male and female mosquitoes consume nectar for their nutritional needs.

Both viruses mainly cycle between mosquitoes and non-human primates.

Common symptoms for both diseases include: fever, headache, rash, joint pain, and muscle pain.

Most ZIKV infections do not cause disease, while most CHIKV infections do.

ZIKV and CHIKV are transmitted by the same mosquito species and cause similar diseases.

Aedes mosquitoes usually bite during the day, with peak activity in the early morning and early evening.

More **infectious disease research** at Los Alamos

http://www.lanl.gov/discover/publications/1663/archive.php

- **A faster way to find new antibiotics**
  "The Mold Rush" October 2015
- **Forecasting flu using internet data**
  "Wikidemiology" May 2015
- **Tuberculosis's antibiotic workaround**
  "Fight of the 21st Century" January 2015
- **Preventing the spread of infectious disease**
  "Biosurveillance" July 2013

from 1663

fun with light and matter

METAMATERIAL "ATOMS" ABSORB AND RE-RADIATE LIGHT LIKE REAL ATOMS, ALLOWING UNIQUE CAPABILITIES FOR IMAGING AND COMMUNICATIONS.

Los Alamos scientist Hou-Tong Chen tests his metamaterial inventions in an anechoic chamber. The chamber is designed to absorb electromagnetic waves and prevent reflections to simulate a wide empty space—effectively, a room with no walls.

CREDIT: Michael Pierce/LANL

IT WAS A VERY DARK TIME IN HUMAN HISTORY. There was no streaming service, no satellite, not even cable. The television set weighed about as much as a Hummer, and you had to physically walk over to it and turn a mechanical knob to change the channel. Programming was beamed out over the airwaves in real time, so if you weren't tuned in at the time the networks chose, you missed your show. And to receive a clear broadcast, you had to manually adjust these big spindly metal antennas: two long, telescoping metal rods and a small metal loop.

Barbaric though it may seem by modern standards, there was something pleasantly straightforward about the whole thing. One could readily see that it had all the proper components for pulling video content from the air. The knob selected the frequency, and those rod and loop antennas grabbed the electric and magnetic components, respectively, of the electromagnetic waves that carried the video stream. You could even see little red, green, and blue pixels on the screen if you looked closely enough.

In his research into advanced electromagnetic-transmission technology, Hou-Tong Chen, of the Los Alamos Center for Integrated Nanotechnologies, pursues the new with a nod to the old. He's inventing a new generation of ultrathin "metamaterial" devices for manipulating electromagnetic waves in the microwave, terahertz, and infrared bands, with the promise of enabling flat, light-weight, and low-cost components for important communication and imaging applications. And at the heart of each device are a bunch of tiny metallic rod and loop antennas.

> the metasurface lens behaves like glass, but without any of the thickness or heft

Fresh take on freshman physics

Every student of physical science or engineering takes a year of introductory physics, which includes a semester on electricity, magnetism, and their joint appearance as electromagnetic waves. It's all 19th-century science, but Chen, and others in his field, are giving it a dramatic facelift for the 21st century.

Electromagnetic waves are comprised of perpendicular, oscillating electric and magnetic fields. Electric fields push and pull on charged particles directly, so electrons in a conducting antenna move back and forth along the antenna as an oscillating electric field passes by. Magnetic fields drive electrons to circulate around a conducting loop antenna when the oscillating field is directed through it. The electrical currents thus formed in the antennas can then be interpreted by an electronic device, such as a television.

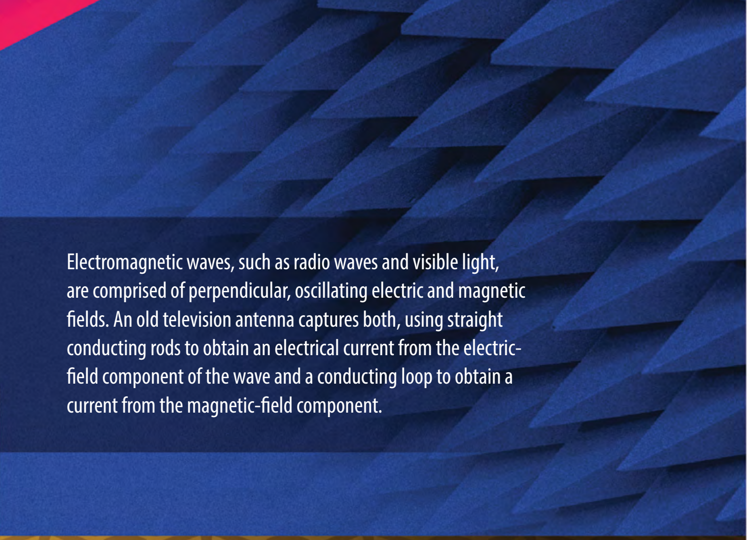
But Chen has a different objective. Rather than using antennas and electronics to make and receive transmissions, he creates arrays of small antenna-like structures to act as resonators, absorbing the energy of passing electromagnetic waves and then re-radiating them—forward, backward, or some other direction—with altered properties. Essentially the same thing routinely happens at the atomic scale, with atoms and molecules acting as resonators, deep inside a thick, bulk material, as when light rays are bent by a glass lens. But his devices are flat and constructed from repeating metallic resonators large enough to be seen with the naked eye, or nearly so. Each resonator is effectively "painted" onto a thin-film substrate, creating a metamaterial surface, or metasurface, to play the same role that atoms and molecules play in normal, bulk-material lenses and other optical devices.

"My 'meta-atom' resonators need to be at least ten times smaller than the wavelength of light I'm using," says Chen. "It's difficult to make them for visible light, with wavelengths less than a millionth of a meter. But for centimeter-sized microwaves or submillimeter terahertz waves, packing thin-film surfaces with resonators is much more practical."

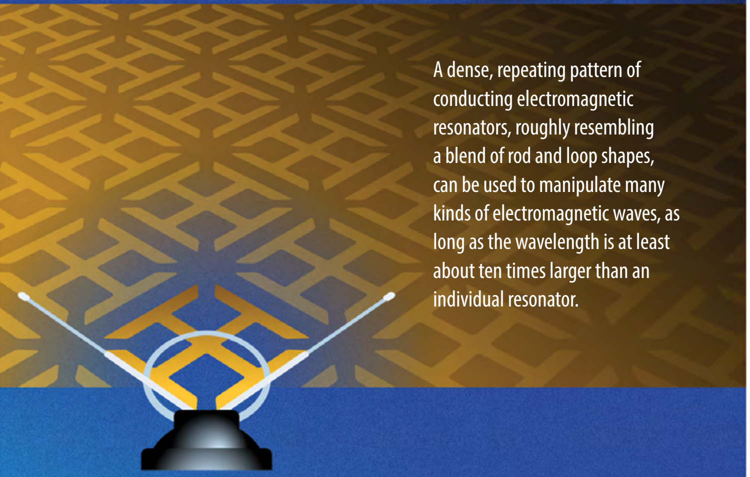
Metasurface monocle

One of the first practical applications Chen pursued with his metasurface resonators was an anti-reflective (anti-glare) film, similar in function to coatings added to prescription eyeglasses. He found that his resonators could be used to alter the phase of electromagnetic waves, such that one wave could be made to have its electric field point downward at the same time and place as another wave's electric field points upward, producing a cancellation. If the system is structured so that this cancellation occurs upon reflection, then violà, the reflection vanishes, and the glare is gone.

Chen experimented with different arrangements of resonators and found that the best results could be obtained by layering two sheets of resonators, with resonators of different shapes on each sheet. At each of the metasurfaces,

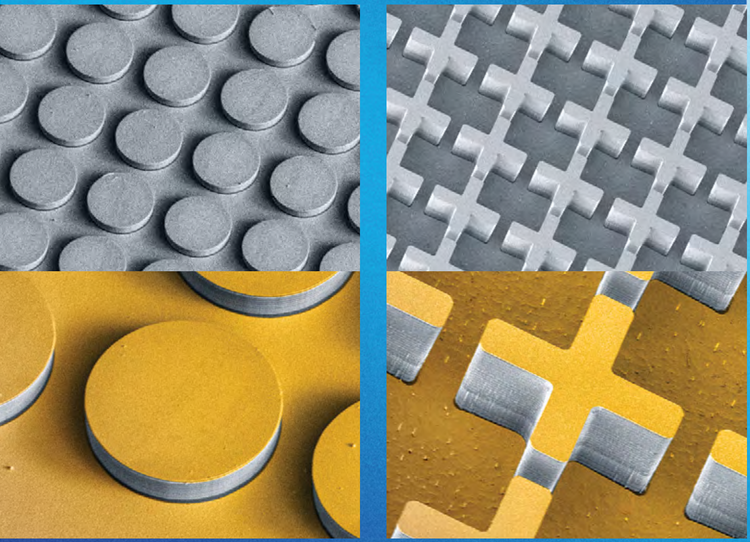


Electromagnetic waves, such as radio waves and visible light, are comprised of perpendicular, oscillating electric and magnetic fields. An old television antenna captures both, using straight conducting rods to obtain an electrical current from the electric-field component of the wave and a conducting loop to obtain a current from the magnetic-field component.



A dense, repeating pattern of conducting electromagnetic resonators, roughly resembling a blend of rod and loop shapes, can be used to manipulate many kinds of electromagnetic waves, as long as the wavelength is at least about ten times larger than an individual resonator.

(Right) An anti-reflective film can be made by stacking two metasurface layers, each with different resonator elements. (Below) This can be accomplished cheaply by creating the two layers, an upper layer extruded from a lower layer. Different extruded resonator shapes yield different results; for instance, the circular extrusion shown produces anti-reflective activity only within a narrow wavelength (or frequency) band, while the "+" shape produces broadband anti-reflective activity across a wide range of wavelengths. Gold coloring indicates the active conducting surfaces.

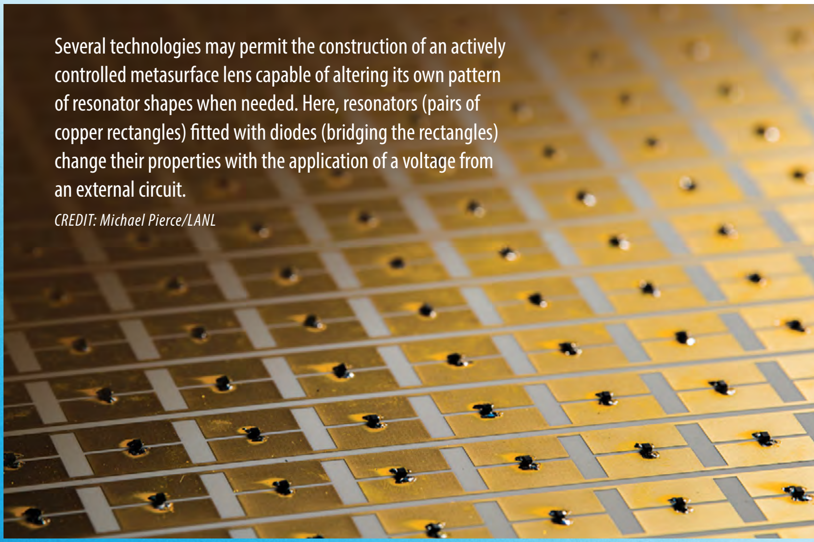


a phase adjustment occurs, producing some waves moving back and forth between the two layers. On the side where the light enters, the system is engineered to produce phase cancellation so little or no light reflects; on the opposite side, phases are tuned to produce nearly 100 percent transmission through the sheets.

Crucially, the anti-reflective metasurface films can be made exceedingly thin. With previous anti-reflective coatings, the phase change is produced while the wave travels through the coating—a miniscule distance for visible light, but an impractically large distance for longer-wavelength signals. With metasurfaces, the phase change is produced directly by the resonators, so no travel distance is needed.

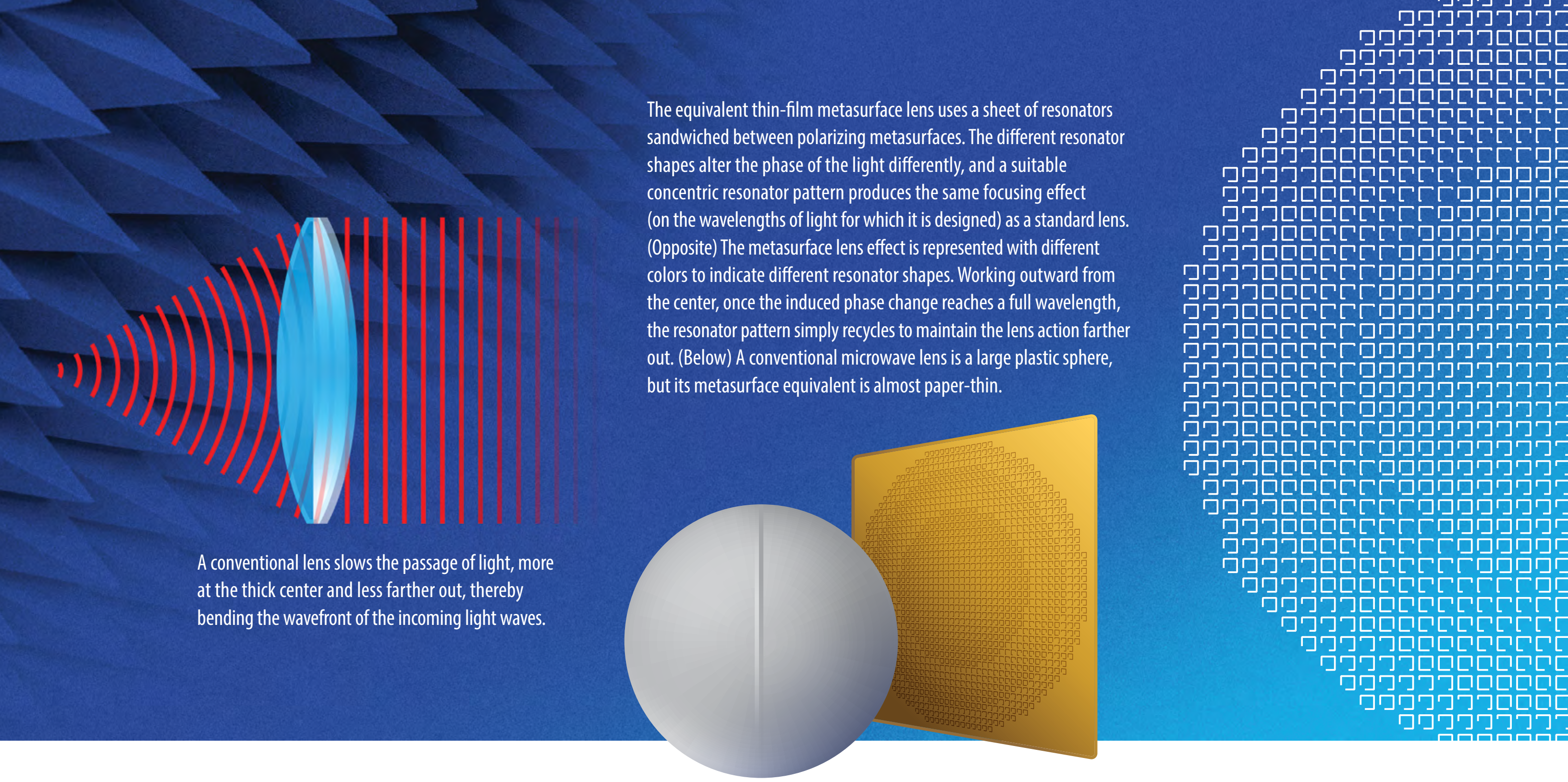
Different resonator shapes produce different results. Square- and circle-shaped resonators, for example, proved anti-reflective only for a fairly narrow frequency of incoming light; that is, they produced a narrow-band anti-reflective effect. With a "+" shaped resonator, however, Chen was able to achieve a much broader-band anti-reflective effect. Other shapes allowed for interesting multi-band effects—anti-reflective for a few distinct frequencies only.

Another glare-control technology ready for a metamaterial upgrade is the polarizer. Polarizers use thin conducting lines to absorb electromagnetic waves oriented in a particular direction (e.g., electric up-down and magnetic left-right) and transmit waves only with the perpendicular polarization. The most familiar application might be as a glare-reduction coating on sunglasses (in this case, for fighting glares produced by the world at large, not by the glasses themselves). Most nuisance glares tend to be caused by light bouncing off of flat surfaces, such as roads and lakes; the light becomes polarized in the same direction every time by the bounce. Polarizing sunglasses filter out the bounced component and let the remaining unpolarized light through, giving the wearer a view of the scene without the glare.



Several technologies may permit the construction of an actively controlled metasurface lens capable of altering its own pattern of resonator shapes when needed. Here, resonators (pairs of copper rectangles) fitted with diodes (bridging the rectangles) change their properties with the application of a voltage from an external circuit.

CREDIT: Michael Pierce/LANL


The equivalent thin-film metasurface lens uses a sheet of resonators sandwiched between polarizing metasurfaces. The different resonator shapes alter the phase of the light differently, and a suitable concentric resonator pattern produces the same focusing effect (on the wavelengths of light for which it is designed) as a standard lens. (Opposite) The metasurface lens effect is represented with different colors to indicate different resonator shapes. Working outward from the center, once the induced phase change reaches a full wavelength, the resonator pattern simply recycles to maintain the lens action farther out. (Below) A conventional microwave lens is a large plastic sphere, but its metasurface equivalent is almost paper-thin.

A conventional lens slows the passage of light, more at the thick center and less farther out, thereby bending the wavefront of the incoming light waves.

Metasurface polarizers, with repeating resonators shaped like thin lines, accomplish roughly the same effect, but can be combined with phase adjustment to produce useful elements of control. By layering two or three polarizing metasurfaces, with resonators rotated by different angles, Chen was able to create a device that fully rotates the polarization of terahertz waves by 90 degrees—useful for materials characterization and polarization-sensitive sensing and imaging applications—both as a transmission device (cross-polarized light is what goes through) and as a reflection device (cross-polarized light is what bounces back). A similar effect can be produced with a thick stack of conventional polarizers, each rotating the wave's polarization by a very small angle until it adds up to 90 degrees, but with metasurfaces, three ultrathin layers stacked together can control phase and polarization with minimal losses.

Chen's lens

"Polarizers and anti-reflective surfaces are great, and anything that can be controlled with thin films has the potential to be a technological game-changer," says Chen. "But my favorite application so far is the metasurface lens."

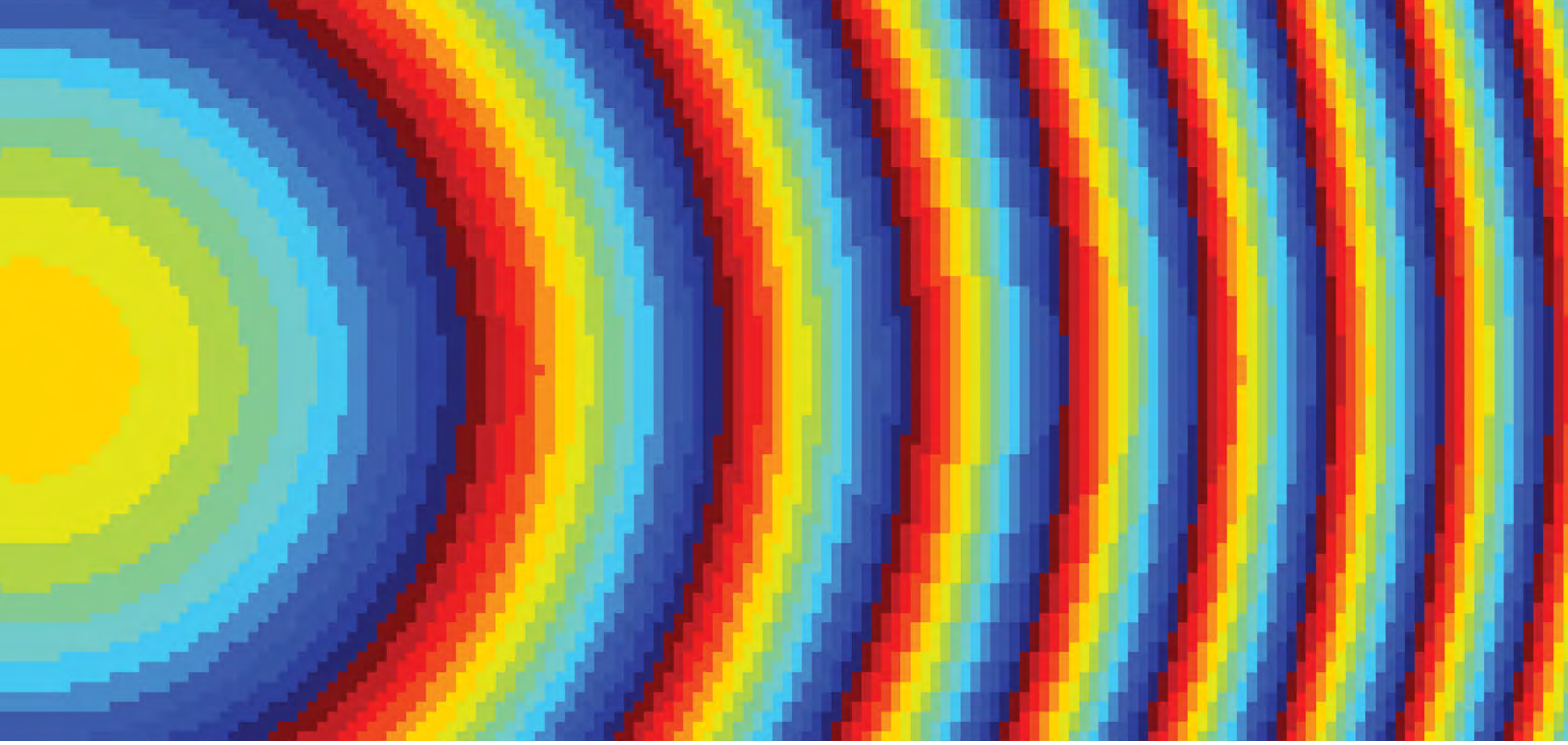
Light can be focused by thick glass lenses or curved reflective dishes. For some applications, these are problematic because lenses and dishes are large and heavy. They generally can't be integrated into lightweight field equipment, and they come at an enormous premium on satellites and spacecraft.

"To beam a signal from, say, Jupiter back to Earth requires a large and heavy high-gain antenna," says Chen. "But if a thin film could do the job, just imagine how much size and weight that would free up for additional systems and instruments on the spacecraft—and how much more we could learn from it." Indeed, after more than a decade of engineering and construction, NASA's 1989-launched *Galileo* spacecraft suffered a malfunction, with its high-gain dish antenna failing to fully deploy. Because of its size and weight, it had to be packaged and self-assembled in space from smaller segments supported by metal ribs, similar to an umbrella, but some of those metal ribs did not unfurl. The problem was ultimately traced to the lubricant that allows the metal ribs to open. A thin-film sheet, however, has no moving parts (and no need for lubricant) and would be immune to this type of problem.

some metamaterial applications seem to jump right off the page

Chen, together with his Los Alamos colleague Abul Azad, set out to build a complex array of resonator shapes sandwiched between two opposite-orientation polarizer metasurfaces. Each shape was designed to interact with the polarizers and produce a different phase change. Chen and Azad arranged the different shapes in concentric rings to behave like a simple, conventional lens—but without any of the thickness or heft.

A conventional lens focuses (or beams) light because light waves travel more slowly through glass than through empty space, interacting along the way with atoms that act like tiny resonators. The thickness of the lens diminishes outward from its center, producing less of a slowdown farther out. The effect is to manipulate the incoming wave front, focusing light inward toward a focal point (or making parallel the light radiating outward from a focal point in the case of beaming). The metasurface lens brings about the same controlled phase changes varying outward from the center: different resonator shapes act like different thicknesses of glass.



And like a deliberately misshapen lens that sends light off to the side, it can focus or beam electromagnetic waves in any direction he chooses, simply by adjusting the arrangement of resonator shapes.

Intention and invention

The ability to control beaming with thin, lightweight components got Chen thinking about what else his metasurfaces might be able to do.

"That's how science and invention work," he says. "With each new thing you discover, you ask what else that new discovery might allow you to do that you couldn't do before."

In the case of the metasurface lens, Chen immediately recognized the potential for steering beams and transmissions in different directions by adjusting the resonator pattern on the fly. If he could create resonators able to respond to some kind of command to change shape, he could then aim transmissions in different directions with a single thin-film lens and no moving parts—no active pointing, no motor drive. The beam goes off in different directions as desired, but the lens stays fixed. This is what he's working on now, and he already has some promising leads. Initial experiments suggest he can rearrange resonator shapes with externally applied electrical signals or laser light. This capability may have a serious technological impact, yet even robust, lightweight, steerable metasurface lenses are probably far from the end of the story.

"With research into novel phenomena like these, some applications seem to jump right off the page, while others only emerge later after we've had more time to reflect," says Chen. One of the jump-off-the-page applications he cites is miniaturization of optical systems. A typical handheld camera lens contains lots of complex and expensive optical components. Something similar goes for transmission and imaging devices at longer wavelengths (e.g., microwave or infrared). Indeed, microwave lenses, for example, are neither glass nor thin; rather, they are extremely large plastic spheres. These and other components should be amenable to replacement with one or more thin-film metasurfaces, at once reducing complexity, weight, size, and cost.

Another readily evident application is terahertz screening, like at airport security checkpoints. Terahertz waves penetrate most materials but are not dangerous the way x-rays are. Metasurface films controlling terahertz waves could make for simple, inexpensive screening systems that could be easily deployed all over the world. Indeed, terahertz systems of all kinds show promise for future technologies and are limited only by the current lack of available components for controlling them—components such as lenses, polarizers, and even anti-reflective films. Chen is working with colleagues across organizational boundaries to expand the Lab's already-extensive portfolio of metamaterial components and technologies.

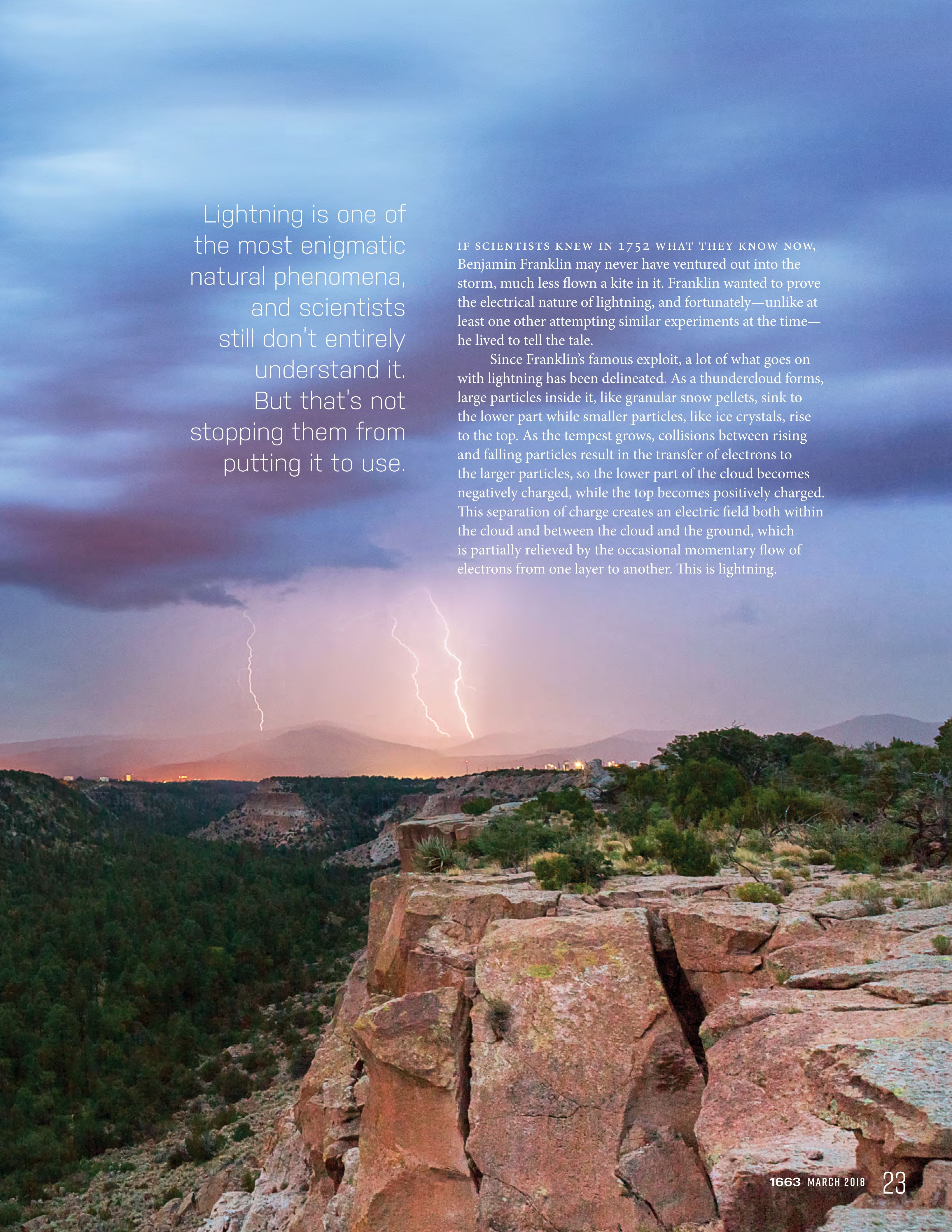
But what about the more-time-to-reflect applications of the future—what might those be? Chen points to the fact that Mother Nature provides a variety of materials with useful properties, but very often they are limited. The index of refraction, for instance, is always positive, meaning that natural materials bend light only in particular ways. But metamaterial refraction of light, such as that from Chen's metasurface lens, doesn't operate by changing the index of refraction of a medium; its resonators are governed by a different principle, allowing it to do things nature's materials can't. As such, the ultimate capabilities of metamaterials and metasurfaces may depend only on human creativity and imagination. What doors might that open?

"I don't know yet," Chen admits. "But the exotic discoveries in metamaterials and metasurfaces so far feed into many, perhaps most, aspects of electrodynamics and optics. That's got to mean something." LDRD

—Craig Tyler

OUT OF THIN AIR

CREDIT: Jim Stein



Lightning is one of the most enigmatic natural phenomena, and scientists still don't entirely understand it. But that's not stopping them from putting it to use.

IF SCIENTISTS KNEW IN 1752 WHAT THEY KNOW NOW, Benjamin Franklin may never have ventured out into the storm, much less flown a kite in it. Franklin wanted to prove the electrical nature of lightning, and fortunately—unlike at least one other attempting similar experiments at the time—he lived to tell the tale.

Since Franklin's famous exploit, a lot of what goes on with lightning has been delineated. As a thundercloud forms, large particles inside it, like granular snow pellets, sink to the lower part while smaller particles, like ice crystals, rise to the top. As the tempest grows, collisions between rising and falling particles result in the transfer of electrons to the larger particles, so the lower part of the cloud becomes negatively charged, while the top becomes positively charged. This separation of charge creates an electric field both within the cloud and between the cloud and the ground, which is partially relieved by the occasional momentary flow of electrons from one layer to another. This is lightning.

Where a lightning flash occurs, the air is literally ripped apart—because air is a poor electrical conductor, for an electrical discharge like lightning to pass through it, the air molecules have to be broken down into ionized plasma—and the temperature spikes to five times hotter than the surface of the sun. A typical lightning bolt comprises two distinct kinds of electrical discharges: leaders, which form the main zigzag, and streamers, which are barely visible tendrils that sprout from the leaders. Leader discharges and streamer discharges are different in terms of charge, length, and duration, with streamers being smaller than leaders in all regards.

Despite breakthroughs in lightning science since Ben Franklin's day, there are still a lot of questions with respect to this most dynamic phenomenon of the natural world. Like what actually initiates a lightning bolt? The electric field in the cloud is not large enough to cause a spontaneous spark. The following three projects at Los Alamos are helping scientists understand the cause of lightning as well as how it can be put to use.

Project One: Searching for a spark

For decades at least, scientists have been trying to shed light on the source of lightning initiation. One theory is positive streamers, which are, in lightning lingo, brief and thread-like ionized paths that usually form inside the cloud, relatively high up, between the negatively and positively charged regions. (They also form between the cloud and the ground, which is temporarily positively charged, having had its electrons pushed away by the negatively charged cloud looming overhead). Scientists first thought that negative streamers initiate lightning, but that theory requires an electric field much greater than what's been measured. Initiation by positive streamers, on the other hand, demands a considerably lower electric field (though still too high), but observations show positive streamers forming after the leader forms, not before.

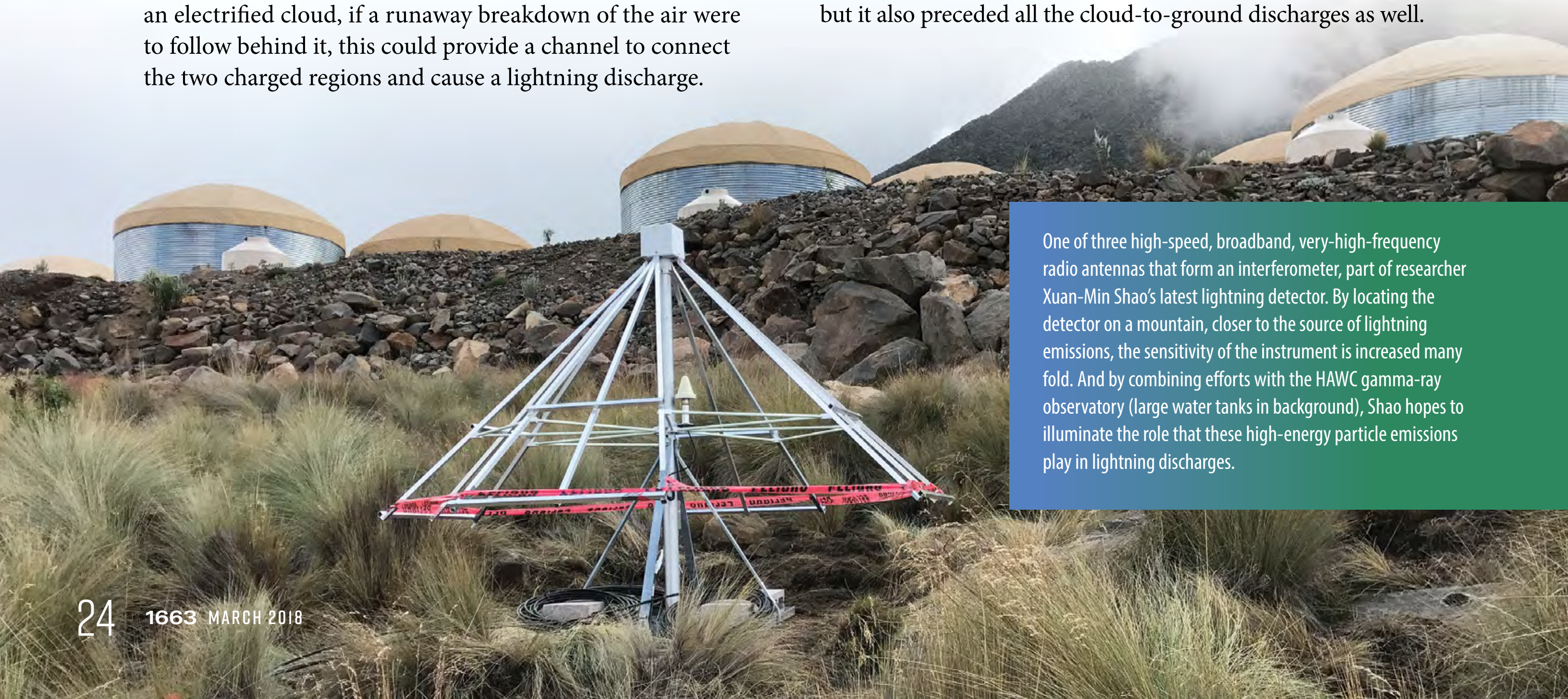
Another theory is cosmic rays. These very-high-energy particles continually bombard the planet, and may, so the theory goes, make the air in their wakes electrically conductive for a fraction of a second. As a cosmic ray travels through an electrified cloud, if a runaway breakdown of the air were to follow behind it, this could provide a channel to connect the two charged regions and cause a lightning discharge. This theory doesn't require as strong an electric field as the positive streamer theory, but as yet, runaway air breakdown has not been observed in association with cosmic rays traveling through thunderclouds.

A third theory that is gaining traction is fast positive breakdown, that is, air breakdown by fast positive streamers. Regular positive streamers are typically slow and weak, whereas fast positive streamers, as their name suggests, are much faster and stronger. They are known to occasionally occur immediately after especially energetic lightning discharge processes, yet their physics isn't well understood. Recently, Los Alamos physicist Xuan-Min Shao and his collaborators observed fast positive streamers occurring in virgin air, immediately before lightning. This prompted a hypothesis for how fast positive streamers might initiate lightning: Although the overall charge of the cloud is inadequate, small regions of very strong electric field may enable the spontaneous formation of fast positive streamers, which could break the air down and result in leader formation.

"These patches of intense electric field, combined with the presence of water droplets and ice crystals in the cloud—which may further increase the field strength—could be enough to get a fast positive streamer started," says Shao.

Most lightning is intracloud lightning, which never comes anywhere near the ground, so to test their theory, Shao and his collaborators are focusing on the sky. They deployed a lightning-mapping array on top of a mountain in Central New Mexico. The array, based on a concept originally introduced by Shao, included a high-speed broadband very-high-frequency (VHF) radiation interferometer, which is the only kind of detector with sufficient temporal and spatial resolution to pick up fast positive breakdown. It works by comparing phase differences between VHF signals received from pairs of spatially separated antennas. The differences are used to back-calculate the direction of the source of the signal, thereby generating a two-dimensional lightning map.

After observing hundreds of lightning discharges the researchers are confident that they're on to something: not only did fast positive breakdown precede all the intracloud discharges, but it also preceded all the cloud-to-ground discharges as well.


One of three high-speed, broadband, very-high-frequency radio antennas that form an interferometer, part of researcher Xuan-Min Shao's latest lightning detector. By locating the detector on a mountain, closer to the source of lightning emissions, the sensitivity of the instrument is increased many fold. And by combining efforts with the HAWC gamma-ray observatory (large water tanks in background), Shao hopes to illuminate the role that these high-energy particle emissions play in lightning discharges.

No other phenomenon has yet been observed to correlate so well. More research is needed before it can be called a smoking gun, but it's looking good so far.

Recently, Shao built and deployed another detector, with the goal of further clarifying how fast positive breakdown works. In addition to visible light and VHF electromagnetic radiation, lightning also produces very-high-energy gamma rays, but the role that they play in the electric charging or discharging of thunderclouds is unclear. The new lightning-detection system includes the same type of VHF interferometers used previously, but this one also has a small gamma-ray detector and a tool to measure VHF polarization, which will reveal the direction of electron movement in a lightning discharge. In addition, the new array has a heavy-hitting neighbor: the High-Altitude Water Cherenkov Gamma-ray Observatory (HAWC, discussed in more detail in "Dark Matter Gets a Little Darker" on page 2). Located atop a mountain in Mexico, HAWC is a collaborative project between Los Alamos and numerous other entities (led by Los Alamos astrophysicist Brenda Dingus), built to study some of the most energetic phenomena in the universe, and Shao's new lightning detector is cozied up right next to it. The plan is that when lightning strikes, HAWC will pick up the gamma emissions (with a million times more sensitivity than the small gamma-ray detector built into Shao's array) while the lightning-detector will provide location, frequency, energy, and timing information.

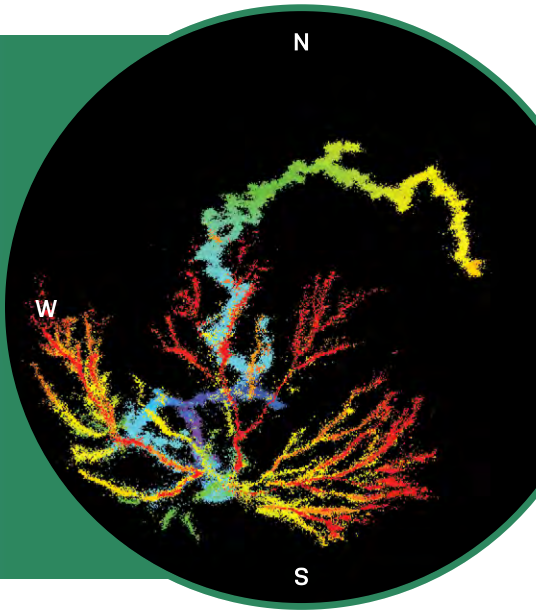
Where **lightning flashes,** the air is **ripped apart** and the **temperature** rises to **hotter than** the surface of **the sun.**

Conveniently, HAWC also detects cosmic rays, so the new setup may be able to shed new light on the cosmic ray question: do cosmic rays disrupt the air's molecular structure enough to initiate a lightning discharge? If they do, Shao's lightning-detection system, working with HAWC, will see it.

Advanced lightning mapping and high-energy particle observations will answer key scientific questions about not just lightning, but other bright flashes as well—the physical signatures of lightning are very similar to those of atmospheric nuclear explosions. By studying lightning, something that is happening all the time across the globe, Los Alamos scientists can learn more about nuclear explosions, which are, needless to say, much rarer, thereby serving the Laboratory's nuclear explosion detection and forensics missions.

Project Two: Illuminating the ionosphere

Thunderstorms happen in the atmospheric layer called the troposphere. Above the troposphere lies the stratosphere, then the mesosphere, then the thermosphere; each layer is defined by distinct temperature changes. But atmospheric layers can be defined by other criteria too: the ionosphere, for example, overlaps parts of both the mesosphere and thermosphere, but is defined by the presence of air ionization due to solar radiation.



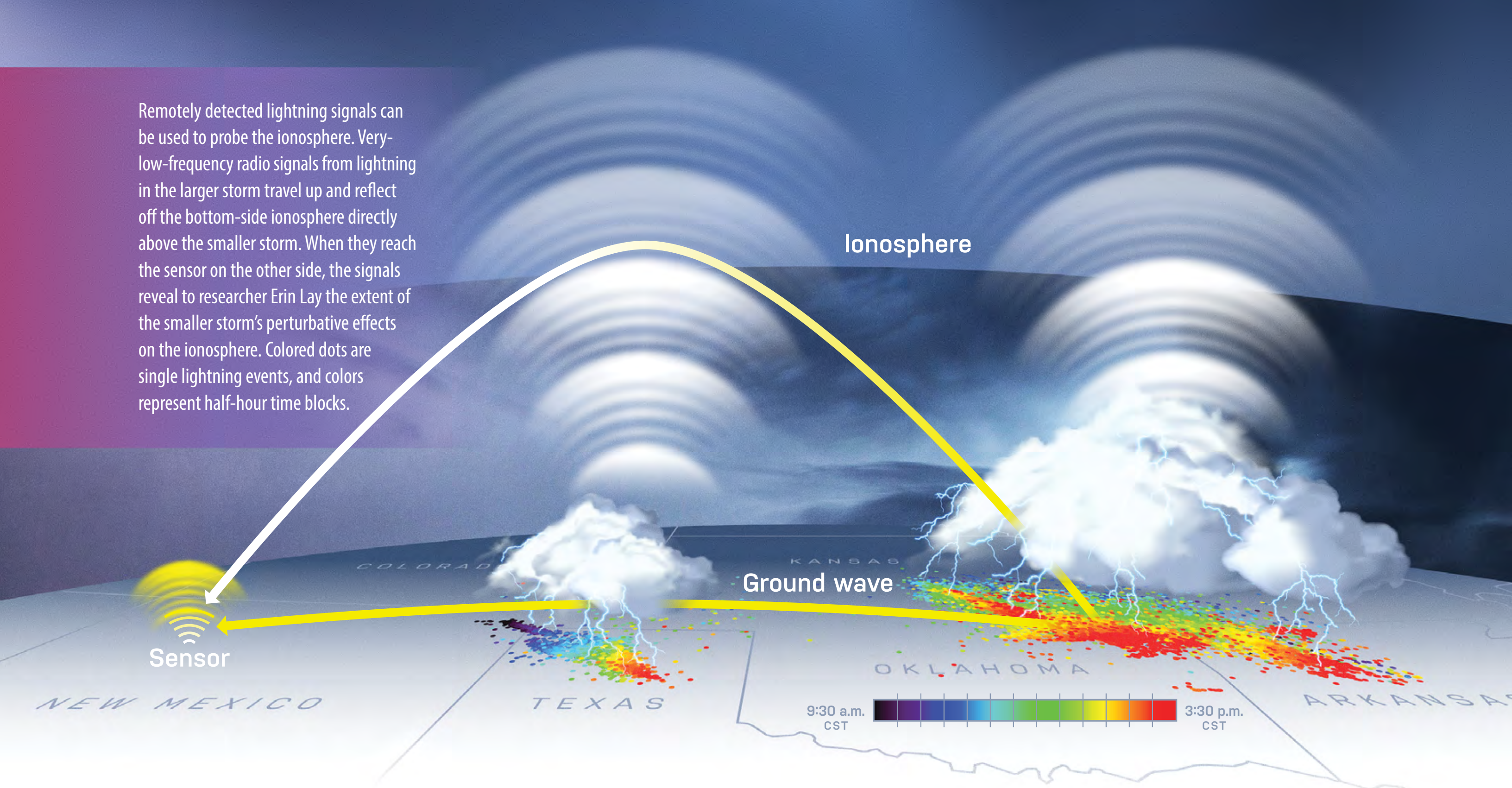
A worms-eye view of a single intracloud lightning discharge in the sky above Los Alamos in May 2017. By comparing phase differences between very-high-frequency radio signals received from spatially separated antennas, the direction of the signal source was calculated. This two-dimensional map spans horizon to horizon, and illustrates the timing (blue to red) of the discharge as it propagated over the course of 0.33 second.

The ionosphere is interesting because it is a plasma, having had the electrons knocked off of enough atoms to result in significant concentrations of ions and free electrons. One of the reasons people study the ionosphere is that it is a key player in sending radio waves beyond the horizon to distant places. The radio waves are sent up from a transmitter, then reflect off of the bottom of the ionosphere and bounce back to Earth-bound receivers situated far from the transmitter.

"The bottom-side ionosphere acts as a guide for electromagnetic waves," Los Alamos atmospheric physicist Erin Lay explains. "It bends them and guides them around the planet. And if it's altered in some way, then how it bends and guides the waves will be altered as well."

Lay specializes in signal propagation through the ionosphere. To understand a received signal and be able to distinguish the source, one has to know what it propagated through. One of the technologies most dependent on the waveguide aspect of ionospheric wave propagation is the very-low-frequency (VLF) communications used by submarines. They need to reliably receive signals from very far away, and anything that interferes with that could spell trouble.

A source of VLF radiation, and one of the most frequent sources of ionosphere perturbations is lightning—specifically, the electric field changes produced by lightning discharges in thunderstorms churning way down in the troposphere. The convection (vertical circulation and heat transfer) and buoyancy (upward force) in a thundercloud produce acoustic waves and buoyancy waves (often called gravity waves, and not to be confused with the astrophysical phenomenon of gravitational waves), which go out in all directions. As these waves propagate upward, toward the ionosphere, their magnitude grows exponentially due to decreasing atmospheric density. But because the electron density of the bottom-side ionosphere is so low, it's hard to measure the perturbative effect of acoustic and gravity waves on the lower ionosphere. Together, Lay and Shao developed a technique to get past that



Remotely detected lightning signals can be used to probe the ionosphere. Very-low-frequency radio signals from lightning in the larger storm travel up and reflect off the bottom-side ionosphere directly above the smaller storm. When they reach the sensor on the other side, the signals reveal to researcher Erin Lay the extent of the smaller storm's perturbative effects on the ionosphere. Colored dots are single lightning events, and colors represent half-hour time blocks.

difficulty, using lightning itself as a kind of radar. Radar works by sending out a signal, then receiving the signal back after it bounces off of something, and interpreting the difference between the two signals to understand the sizes and locations of the things from which the signal bounced.

Lay and Shao's method requires there be two separate storms—one to perturb the ionosphere above it and the other to send lightning VLF signals that reflect off the perturbed region and, once they reach the sensors, reveal the extent of the perturbation they passed through. The proof-of-principle study showed that the already low electron density in the lower ionosphere above the storm was further reduced by 60 percent. This project used a Los Alamos sensor network that Shao helped establish 20 years ago to study lightning and is based on a VLF radio propagation model developed by Shao and his colleagues.

What made the lightning-as-radar project possible was a breakthrough data-processing technique. This technique compares the amplitude of the portion of the lightning radio signal that travels along the ground, undisturbed by the ionosphere, to the amplitude of the signal that is reflected off the ionosphere to reveal how much of the signal was absorbed by the ionosphere. It also uses the time delay between the two signals to indicate the altitude of the bottom-side ionosphere. These measurements reveal to the scientists what the ionosphere looks like above the perturbative storm, just like radar reveals to a pilot what lies beyond the clouds.

Thunderstorms and lightning aren't the only things perturbing the ionosphere that are of interest to scientists. There are other hazardous phenomena, including earthquakes, meteors, and nuclear explosions, whose perturbative potential scientists need to understand. But there's yet another dramatic player in the lightning-as-a-probe ensemble. With temperatures hotter than the surface of the sun and signatures similar to nuclear detonation, what could possibly make studying lightning more dramatic? How about erupting volcanoes?

Project Three: Probing the plume

Los Alamos atmospheric physicist Sonja Behnke was studying lightning when she fell into Alaska's Redoubt volcano. Well, she fell into *volcanology*, to be precise, and it began at Redoubt. As a graduate student, while developing her lightning research, she was offered an opportunity to study volcanic lightning on Redoubt. She accepted and then continued to pursue volcanic lightning during her postdoctoral training, during which a serendipitous series of events helped light her path forward. She joined a team in Florida under aspirations of studying volcanic lightning in Central America. But disappointingly, that project fell through, prompting Behnke to seek out new horizons. Fortune finally landed her at the foot of Sakurajima volcano in Japan, where she studied a peculiar kind of lightning associated with explosive volcanic eruption. Now she is collaborating in the development of a volcano-monitoring system based on that peculiar volcanic lightning.

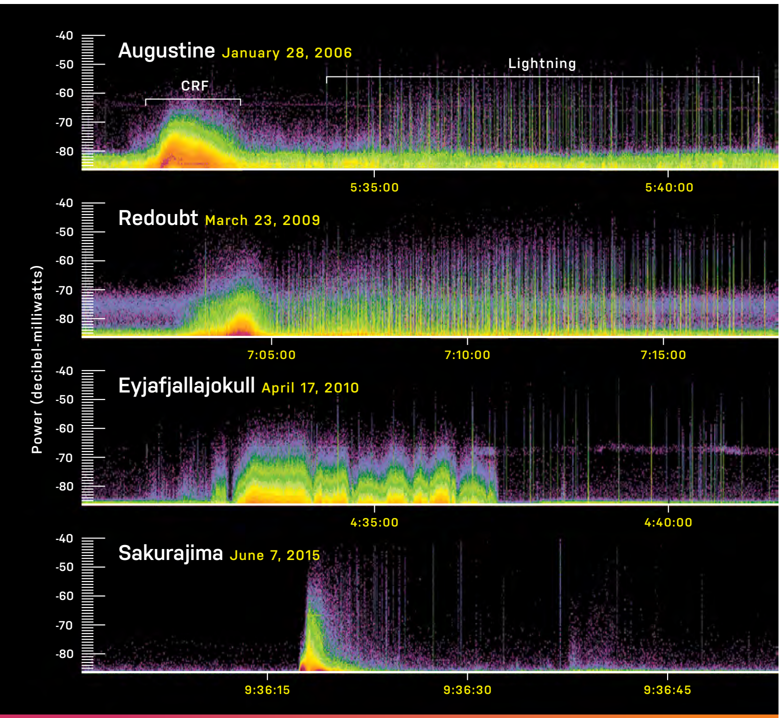
Humans are **fascinated** by lightning, **intimidated** by it, and **motivated to understand** it.

Contrary to popular perception, it's not obvious when a volcano is about to erupt. Volcanoes are often remote, far from human eyes and ears, and their tops can be shrouded in clouds. So, with no one to see or hear an eruption, there's no one to raise the alarm. And yet, an alarm system is warranted, because when a volcano erupts, even a remote one, it poses a major hazard.

"Some people think lava is the main hazard," explains Behnke, "but an ash plume poses much more danger, particularly to aircraft. Because it's slow, lava isn't actually much of a hazard, and the kinds of volcanoes that produce lava don't generally produce ash plumes—they are different types of events. An ash plume is fast and sudden and can extend tens of thousands of feet into the air. It's a serious problem."

In 2010, in response to the relatively small eruption of Eyjafjallajökull volcano in Iceland, 20 countries decided that the risk to human lives was great enough to warrant extreme disruption of European air traffic, and ordered their airspace closed to commercial jets. If a jet flies through an ash plume, its engines may fail. The mechanics get mucked up, the air intakes get suffocated, and the entire engine becomes coated in volcanic glass. It's not uncommon for commercial flight paths to pass over volcanoes, and if it's nighttime, or cloudy, a pilot won't see an ash plume—which may not have been there hours or even minutes before.

On Sakurajima, Behnke set up an elaborate lightning-mapping array to collect VHF data that would tell her, in addition to the frequency and duration of radiation emissions, the location and size of the source as well. She knew that the onset of an explosive eruption is accompanied by a powerful burst of continuous radio-frequency (CRF) radiation that lasts too long to come from a normal lightning discharge. The theory was that the source of the CRF burst was, in fact, many small leader discharges happening in rapid succession near the vent of the volcano as the first ash plume bursts forth. If the plume carried an inherent net charge, the theory proposed, then that could facilitate small leader discharges between the plume and the ground. But Behnke's data showed that something else was going on.



Continuous radio-frequency (CRF) emissions at the start of an explosive volcanic eruption are distinct from radio emissions produced by later volcanic lightning discharges. A CRF burst has been measured during every volcanic eruption that researcher Sonja Behnke has studied. She is working on the development of a volcano-monitoring system, based on these CRF emissions, that will help keep aircraft out of dangerous volcanic ash plumes.

The CRF burst was indeed coming from a rapid-fire series of discharges near the vent, but each individual discharge was too brief to be a leader, and the entire burst was happening before any electrical charge in the plume could be detected. Further, leaders, even small leaders, are at least tens of meters in length, while the discharges Behnke measured were only a few meters at most. So Behnke concluded that the CRF burst couldn't come from leaders. She decided streamers, rather—those filamentary streaks that branch off of leaders—were more likely.

Behnke has seen these streamer-like discharges in every volcanic eruption she looked at. They have no counterpart in thunderstorms, are unique to the initial moments of explosive volcanic eruptions, and can be detected up to 100 kilometers away. So the phenomenon is a good candidate for an eruption monitor.

There are other technologies as well: seismometry, infrasound, radar, and satellite imagery are each useful for volcanic monitoring but are each fraught in one way or another. Lightning observation, on the other hand, may just be the stroke of genius needed to protect planes, pilots, and passengers alike.

Lighter and brighter

A lot of lightning studies originated from atmospheric nuclear-detection studies. The two things, are, after all, quite similar. Because of these similarities, it makes sense that Los Alamos scientists would study lightning. It's a tremendously convenient natural proxy.

But aside from mission-driven applications, there's strong basic-science rationale for studying lightning. It is ubiquitous to the human experience; one can't help but be fascinated by it, intimidated by it, and motivated to understand it. As the intrepid Mr. Franklin's derring-do demonstrates, people will go to great lengths to tame nature by figuring out how it works.

In that spirit, Shao, Lay, Behnke, and their contemporaries are inventing tools and venturing into the storm, rather than staying in and peering out the window. Well, actually they *are* staying in, well out of literal storms (putting their instruments in place when there isn't a storm, then waiting for the storm to come), because they know more than Ben Franklin did. But they are intent on taming the figurative storm, the storm of the unknown, and thankfully, their tools are far more sophisticated, and a good bit safer, than a kite with a key on a wire. LDRD

—Eleanor Hutterer

FRENZIED FLOW

Fluid mechanical studies of turbulence allow computer models to predict the behavior of complex dynamical systems, from tiny fuel capsules for fusion experiments to supernova explosions. But Los Alamos scientist Kathy Prestridge recently discovered two regimes in which the models and computer codes might not be getting it right.

"MY JOB IS TO BREAK THE MODEL," says Kathy Prestridge.

An aerospace and mechanical engineer by training, Prestridge spends her days attacking one of the Lab's most foundational scientific challenges: predicting the motions of fluids. The model she refers to is a collection of equations, computer codes, and best-fit approximations governing the behavior of fluids under extreme conditions, like those deep inside a nuclear weapon, a fusion reactor, or a star. She's on a mission to understand fluid flows and reveal the model's flaws.

Fluid dynamics, or the motions of liquids and gases, manages to be unexpectedly baffling, even in everyday situations. When a fluid flows smoothly, it can be understood by mathematically dividing it into a stack of parallel flows, as if the fluid passed through an egg slicer. But when a flow is just a little more energetic, it can become turbulent, churning and swirling in unpredictable ways. The difference is like that between an ocean wave rolling and an ocean wave crashing.

Even for something as pedestrian as pouring cream into coffee, the equations that govern the fluid dynamics are simply too difficult to solve, even with a powerful computer. Little motions that deviate from computer-model predictions quickly balloon into eruptions and vortices that can end up dominating the whole flow. In fact, some scientists would argue that more is known about the interior of a black hole—a region where no experiments have ever been conducted and, even if they were, their outcomes could never be observed—than about cream mixing into coffee. Or smoke from a snuffed-out candle. Or a gust of wind.

Despite decades of effort to remedy this deficiency, models of turbulent flows, especially those in extreme environments, still don't capture all the relevant physics. Hence Prestridge's desire to break the model: she must find where the current model fails so that it can be fixed or improved—or at least have its weaknesses properly identified. And just recently, she succeeded. She broke the model. Twice.

What little whirls are made of

Much of human understanding of turbulence derives from a 1941 theory by Andrey Kolmogorov (the "K41" theory). He described a turbulent flow by adding to a large-scale flow velocity (e.g., the overall flow of a river) a bunch of smaller-scale velocities (e.g., patches of whitewater). The idea was that whirls of fluid, called eddies, would spin off from a turbulent flow, siphoning energy away from the original flow to do so. As one eddy pushes into the surrounding fluid, it spends its energy spawning other, smaller eddies, which produce still smaller ones after that. Eventually, far enough down the chain, a great many tiny eddies combine to produce fluid moving in every direction equally—a property known as isotropy. These isotropic movements ultimately give their energy to movements on the molecular scale, generating heat according to the viscosity of the fluid. The heat then dissipates into the surrounding environment. Another early contributor to turbulence theory, Lewis Fry Richardson, in the book *Weather Prediction by Numerical Processes*, put it this way:

Big whirls have little whirls that feed on their velocity,
and little whirls have lesser whirls and so on to viscosity.

Early models of turbulence adopted the K41 big-whirls-little-whirls paradigm, and many modern models are still based upon that foundation. The trouble is, detailed measurements reveal that it's not actually true for many of the flows that are important to Los Alamos research. Small-scale fluid motions produced by the cascade of whirls are not isotropic, not even on average. And as Prestridge's team would discover, the energy doesn't always flow from larger whirls to smaller ones. The reality is much more complex, but it takes some serious advanced-measurement capabilities to see it.

Stimulant, depressant, or carcinogen? Whatever your vice, turbulence, in which fluids flow chaotically rather than in smooth parallel layers, is a part of it.

Prestridge's research facility includes a turbulent mixing tunnel—in which a downward-pointed jet of fluid emerges from a pipe into a surrounding fluid—instrumented with technology that's the envy of the fluid-dynamics community. First, she uses planar laser-induced fluorescence (PLIF), which, after an initial laser measurement and a great deal of subsequent mathematical analysis, provides a detailed map of the variations in fluid density throughout a wide horizontal band spanning the jet's wake and the surrounding fluid. It subdivides that band to a resolution of 41,000 tiny patches of fluid. On top of that, she uses particle image velocimetry (PIV) to track the motions of microscopic tracer particles in the flow. A pair of back-to-back images shows how the particles move in a very short time, allowing Prestridge to compute their instantaneous velocities. That allows her to assign a tiny, unique arrow to each of the 41,000 patches of fluid, in addition to each patch's PLIF-derived density.

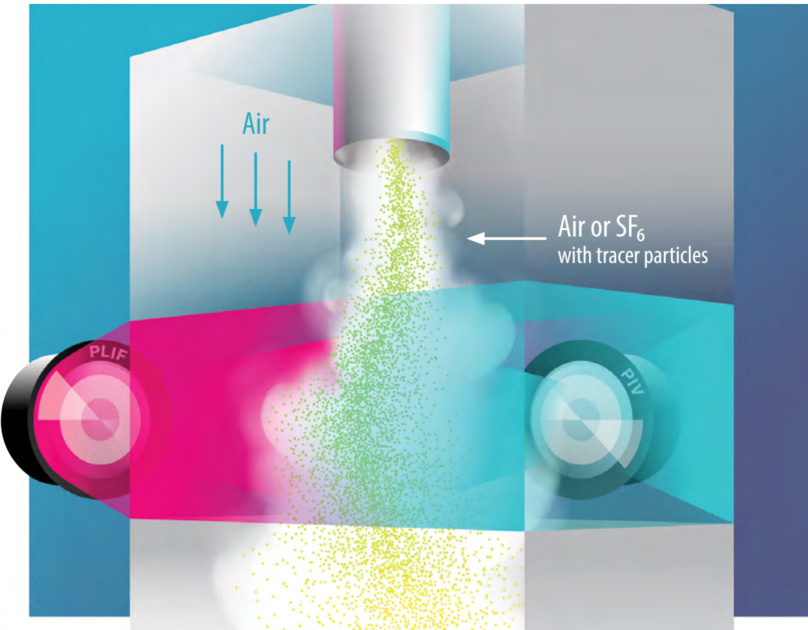
IT TAKES SOME SERIOUS ADVANCED-MEASUREMENT CAPABILITIES TO SEE WHAT REALLY HAPPENS

In previous experiments throughout the research community, it was always either-or: PLIF for densities or PIV for velocities, but not both. The only way to get both was to do the experiment twice. But because turbulence is notorious for producing inherently random variations from one trial to the next, researchers couldn't assume that the observed densities actually corresponded to the observed velocities. Now, in Prestridge's experiments, they can. Densities and velocities are measured together in all the same patches of fluid at the same instant. This means, for the first time, she has detailed information on all the small-scale motions across the flow. It is no longer necessary to assume it's isotropic.

More than that, Prestridge and her team take all three images—one PLIF and two back-to-back PIVs—10,000 times in succession during each trial to obtain comprehensive statistics on the densities and velocities of the fluid as conditions vary within the turbulent flow. That's three high-resolution measurements taken 10,000 times across 41,000 discrete locations in the flow, for anyone keeping count. And they do all that at multiple locations downstream from where the jet emerges from the pipe. Then they do the whole experiment again with a different fluid.

What big whirls are made of

The initial experiment involved a stream of air, laced with tracer particles, exiting the end of a pipe into a tunnel also filled with flowing air. This type of experiment is consistent with the "Boussinesq approximation" often made in fluid dynamics: that there is effectively just one uniform fluid, in this case air, rather than multiple fluids with different densities mixing. (The approximation is useful, for example, when considering ocean currents and not wanting to get bogged down with variations in salt content from one patch of seawater to the next.) The air-on-air Boussinesq flow experiment yielded rich PLIF and PIV data sets, but the major surprise came from Prestridge's subsequent non-Boussinesq flow experiment.



Turbulent mixing tunnel experiments at Los Alamos inject various fluids infused with tracer particles into a surrounding fluid medium. An enormous number of density and velocity measurements are made at multiple distances downstream from the injection point by planar laser-induced fluorescence (PLIF) and particle imaging velocimetry (PIV), respectively.

In that experiment, a stream of sulfur hexafluoride—an inert, nontoxic gas four times denser than air—entered the air-filled tunnel. This time, the data revealed a previously unobserved phenomenon called "negative production of turbulent kinetic energy" (TKE), which utterly upended the prevailing K41 paradigm. It meant that, near the centerline of the flow, small-scale eddies were delivering energy to large-scale fluid movement, instead of the other way around. Subsequent analysis revealed that the small-scale eddies were actually deforming and stretching into larger eddies—a mechanism for transferring energy that's not included in K41. Being the first to conduct an experiment with strong density gradients and simultaneous, fine-scale, across-the-flow density and velocity measurements, Prestridge's team was the first to observe the effect.

COMPLEX MIXING IN FUSION EXPERIMENTS IS DIFFICULT TO RESOLVE WITH CURRENT CODES

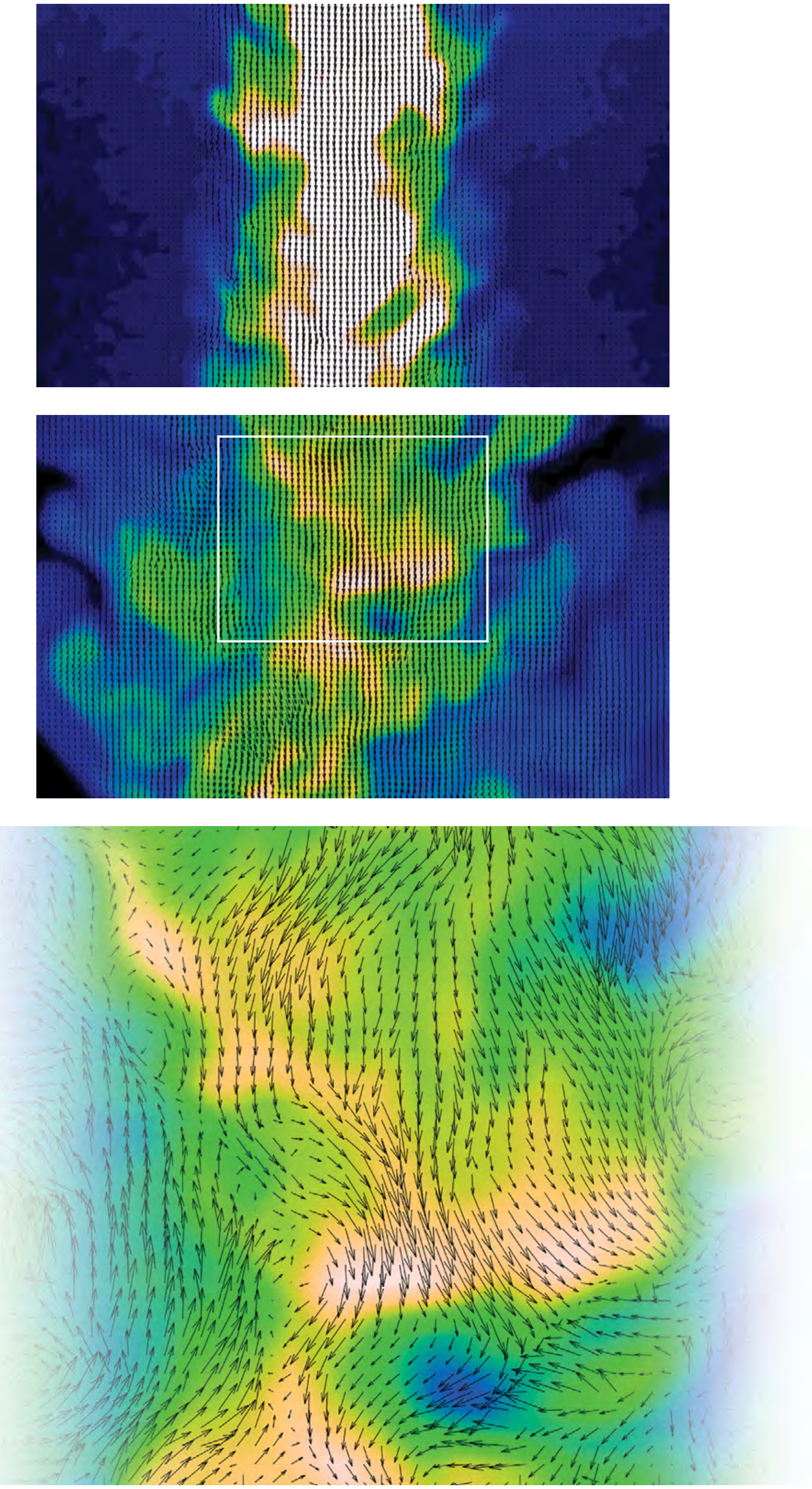
The implications are striking. More than just a curiosity, negative production of TKE is evidently an essential aspect of non-Boussinesq flows and one not accounted for in current models and codes. Moreover, the effect would be amplified in extreme pressure, temperature, and density conditions—as in the nuclear-driven flows studied so extensively at Los Alamos.

"Right off the bat," says Prestridge, "it is critical to figure out if there's something new here that our scientists need to know about turbulent flows when a nuclear weapon is detonated."

Yet it's not just about nukes. Fusion-energy technology, in particular, is vulnerable to complications from turbulent fluid dynamics, and there are many possible reasons why "ignition"—a self-sustaining fusion reaction that generates more power than it consumes—remains elusive at advanced facilities, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory.

"The strong density gradients and shocks present in NIF experiments are likely to induce all sorts of mixing," says Prestridge. "It's difficult to resolve with our codes and predict with our current models."

Turbulent mixing effects are everywhere, and, in a way, even the elemental makeup of the universe hangs in the balance. Many chemical elements are created during the supernova explosions of white dwarf stars. These stars may well have deep plumes of stellar matter with complex mixing under the surface just prior to detonation, causing non-Boussinesq dynamics to influence the outcome. If scientists can't predict the dynamics of the explosion, they will also be unable to predict the abundances of the elements blasted into space or the corresponding chemical evolution of galaxies. This makes astrophysicists very interested in turbulent flow models.



Density and velocity fields from a turbulent mixing tunnel experiment: The upper two images show conditions at different locations, one just below the exit nozzle and the other eight times farther downstream, where the mixing is more pronounced. Colors represent densities: Black is pure air, and tan is the injected fluid, sulfur hexafluoride (SF_6), which is denser than air. Blue and green represent different degrees of mixing, with blue representing mostly air partially mixed with SF_6 and green representing the opposite. In the lower image, zooming in reveals vector arrows indicating the velocities of tracer particles in the flow. Swirling turbulent flow vortices have been made more evident in this image by subtracting the time-averaged flow velocities from the instantaneous ones.

Another shock

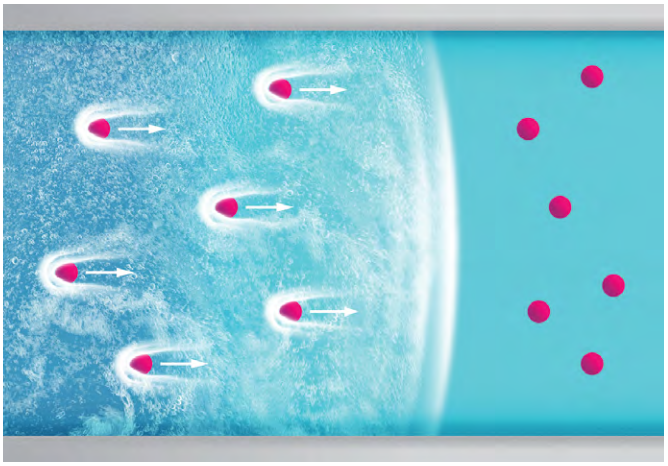
Not one to be satisfied with merely breaking a turbulence model central to nuclear technology and exploding stars, Prestridge went ahead and broke another. This time, her target was particle acceleration induced by drag from a passing shock wave. A shock wave is supersonic, and naturally, being hit with one represents a distinctly unsteady type of flow. This contrasts with the steady flows normally studied to predict drag on objects such as airplanes or golf balls.

> ALL THE MODELS PREDICT SLOWER-MOVING PARTICLES THAN WHAT YOU GET IN REAL LIFE

Prestridge's team suspended micron-sized (millionth of a meter) spherical particles in air within an apparatus called a horizontal shock tube and then sent a shock wave down the length of the tube. The particles, initially still, accelerate sharply in response to the passing shock, chasing it down the tube. The rushing air drags the particles forward, similar to a leaf being whipped up in the wind or, in reverse, a skydiver reaching terminal velocity. A drag coefficient is used to quantify the strength of the drag, and, wouldn't you know it, Prestridge discovered that the drag coefficients in the models were all wrong. In particular, they were too small.

As the star Zeta Ophiuchi (center, blue) speeds leftward through a gas of interstellar matter, its stellar wind produces a bow shock (pink), similar to what lies ahead of a supersonic jet. New Los Alamos research shows that particles caught up in such a shock wave are accelerated more rapidly than previously thought.

CREDIT: NASA, JPL-Caltech, Spitzer Space Telescope



Los Alamos shock-tube experiments operate with micron-sized particles suspended in a gas-filled tube, along which a shock wave propagates. Post-shock particle velocity measurements allow researchers to determine the drag coefficient, which quantifies how strongly the shock wave drags the particles forward (in this case, into their own wake).

"The steady-flow models and the only partly relevant unsteady-drag models out there get it wrong," says Prestridge. "The accelerations they predict are too low, meaning that their predictions yield slower-moving particles than what you get in real life."

Not surprisingly, bits of shock-accelerated particulate matter creep up in a lot of the same settings where the behavior of non-Boussinesq flows is important, including nuclear technology and astrophysics. For example, for many energetic astrophysical phenomena, such as expanding supernova remnants, it is valuable to predict how dust particles will move in the presence of a shock wave.

New modeling will have to accommodate the non-Boussinesq flow and unsteady-drag data so that computational fluid dynamics codes can be updated, science advanced, and technology improved. Fortunately, at Los Alamos, Prestridge is able to collaborate with colleagues doing a variety of experimentation, simulation, and modeling, all in one place. So after breaking the model, she can also have a hand in fixing it.

—*Craig Tyler*

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Floy Agnes "Aggie" (Naranjo Stroud) Lee is a radiobiologist who began her career as a hematologist at Los Alamos. A New Mexico native, she graduated from the University of New Mexico, then joined the Laboratory to study the effects of radiation on cells. In this capacity, she helped evaluate scientists Alvin Graves and Louis Slotin after a 1946 accident in which Slotin received a fatal dose of radiation. Lee left Los Alamos to earn a Ph.D. at the University of Chicago and joined such prestigious institutions as Argonne National Laboratory and NASA's Jet Propulsion Laboratory before returning to, and eventually retiring from, Los Alamos as a radiobiologist in the Lab's Mammalian Biology Group. [See "Women Scientists of the Secret City" in the October 2017 issue of *1663*.]

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