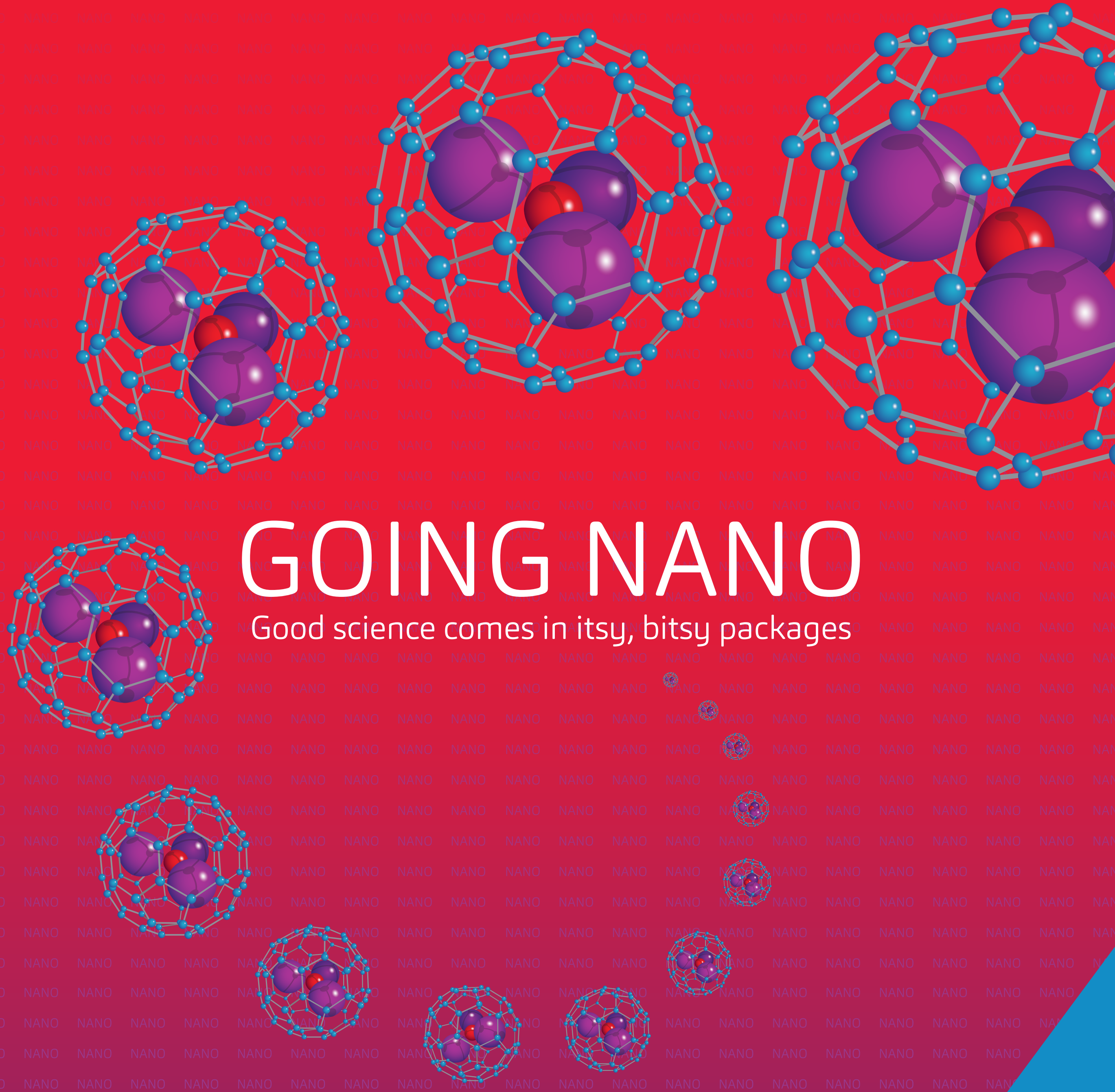
fields

SCIENCE, DISCOVERY & MAGNETISM



GOING NANO

Good science comes in itsy, bitsy packages

- **SEX AND THE SPINELESS**
  Learning from worm pheromones
- **HIGH FIELDS GET PERSONAL**
  Magnet research feels right at home
- **THE FINE ART OF SCIENCE**
  Inside every physicist hides a Picasso

SUMMER/FALL 2017

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fields is produced at The National High Magnetic Field Laboratory (National MagLab) with the support of scientists around the world. Our goal is to show both doers and lovers of science some of the very cool things researchers discover about our world using high-field magnets.

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FIELD TRIP

SIMULATING THE SUN

By manipulating plasma with magnets, scientists are creating the same kind of energy produced by stars.

BY KRISTIN ROBERTS

It's the stuff of science fiction movies: a futuristic-looking device that harnesses the power of the stars to yield unlimited electricity. Yet this storyline is coming to life now at the Institute of Physical Science in Hefei, China, where an impressive instrument generates power by controlling nuclear reactions.

The Experimental Advanced Superconducting Tokamak (or EAST) is a 400-ton machine composed of more than 10 complex parts that fill an area the size of three tennis courts. To understand what it does, we first have to have a little refresher on the most common state of matter in the universe — plasma.

Plasma is a charged gas found in the sun and other stars, but also in neon signs, florescent light bulbs and certain televisions. Unlike other gases, plasma can be influenced by electric and magnetic fields. And when plasma particles are heated up and collide, they can (like the sun) produce massive amounts of energy.

Using EAST, researchers are trying to create this kind of energy with the help of powerful magnets. At the center of the machine are more than a dozen 6-tesla, ring-shaped superconducting magnets that keep the plasma contained. Another set of magnets, oriented perpendicularly to the first, push the charged particles in the plasma toward each other, encouraging those critical collisions — known as fusion — that create the energy.

But this entire plan only works if the plasma can be heated to ultra-high temperatures — temps about 80,000 times hotter than lava. To do that requires a complex injection heating system and other specialized equipment.

Scientists are making progress. When EAST created its first plasma in September 2006, it generated an electrical current of 200,000 amps for three seconds at a temperature of about 20 million degrees Celsius. About a decade later, the machine reached 400 kiloamps for 102 seconds at temperatures up to 50 million degrees Celsius. In the next 15 years, scientists hope to produce steady-state operation of 1,000 seconds with plasma heated to 100 million degrees Celsius.

These ambitious goals are all part of the world's biggest fusion energy project, ITER. Based in France, ITER is a 35-country collaboration to build the world's largest tokamak and change the future of energy. EAST serves as a test bed for ITER, laying a foundation for the ITER tokamak to create 500 megawatts of power (enough to power 250,000 homes for about 10 minutes), all from fusion. Now *that's* a sci-fi fantasy come true.

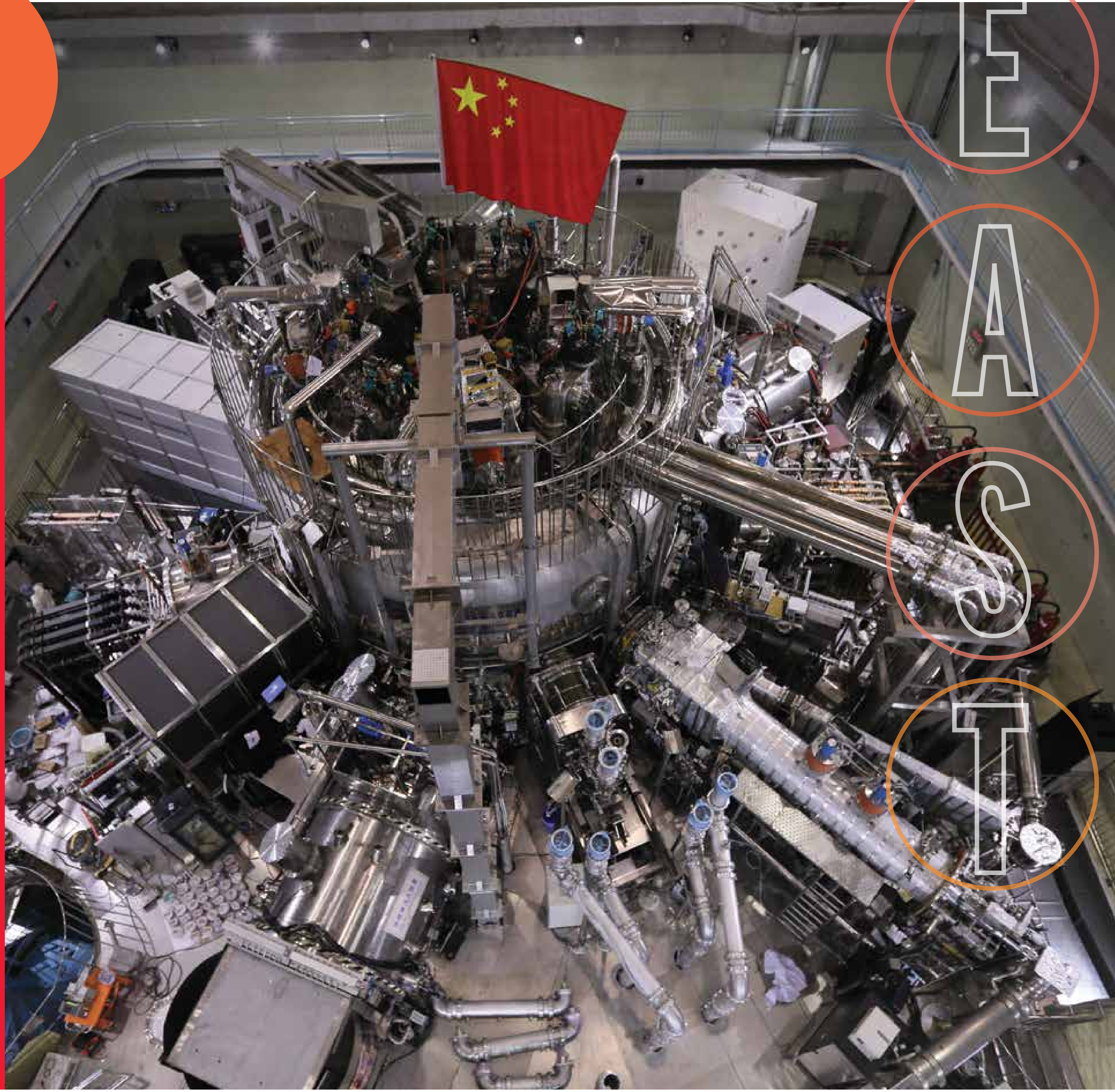


Image credit: Institute of Physical Science

ORIGIN STORIES

Jim Cleaves gets down to earth about how life began on our planet.

Recently, Henderson "Jim" Cleaves, a geochemist with the Tokyo Institute of Technology, visited the National MagLab to do research and to talk on camera about his work. Of course we threw in a catch: He had to explain it in two minutes! We recorded two takes of those interviews, one for scientists (with MagLab physicist Julia Smith asking the questions) and one for the masses (with MagLab Public Affairs Director Kristin Roberts). Read Cleaves' "light" version of his out-of-this-world research below. For the more technical version, visit fieldsmagazine.org to watch the conversations online.

KR: **So tell me: What do you study?**

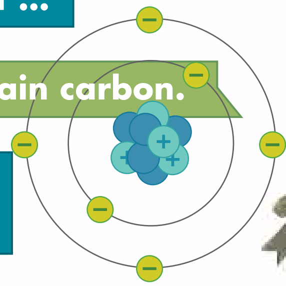
JC: **I study how life might have started on Earth.**

That sounds really big and powerful! How do you tell how life might have started on Earth?

We think that it started when there was some collection of organic compounds that came together in the right setting and started making copies of themselves.

When you say organic compounds you're talking about ...

Things that contain carbon.



Do you look at organic compounds that are in my life, or at fancy compounds I've never heard of?

We study all kinds of organic compounds, some that you probably are familiar with — things like amino acids that they sell in health food stores or are in the foods you eat. Some of them are a little more exotic. Some of them we make ourselves — things that maybe have never existed anywhere before: They're new. There are just so many possible organic compounds that some of them are inevitably going to have never existed before.

Image credit: Stephen Bilenky

How do you decide which ones to look at?

That's a good question! Part of what we do is look at what we find in the natural environment, particularly in things like meteorites. These are things that are left over from when the solar system formed, and we think that is the kind of organic material that was available for life to start. It seems like a good place to look.

Do you think of meteorites like little time capsules?

That's right.

What kind of organic compounds exist in the meteorites?

So many kinds, and that's part of the reason why we're here. There are instruments here that allow us to understand what these maybe millions of types of organic compounds are.

TIME'S UP!

HIGH FIELDS AT HOME

BY KRISTEN COYNE

ILLUSTRATION BY CAROLINE MCNIEL

A lot of the research conducted in powerful magnets ends up having a powerful effect on our day-to-day lives. Here are some examples of ways high-field research across the globe is making our lives safer, greener, more productive and more efficient. For links to details on this research, visit **fieldsmagazine.org**.

1 SOLAR ENERGY

Using high magnetic fields, scientists are constantly inventing and exploring new materials. In some materials, including atomically thin semiconductors and crystals with novel structures, they have observed light-absorbing properties that suggest future technological applications in solar energy and lighting.

Where: **Nijmegen National Laboratory, National MagLab/Pulsed Fields**

2 GREENER GRIDS

Engineers are testing novel ways to manufacture high-temperature superconducting wires that will make them cheaper, more practical and more reliable for use in industrial motors, power cables, power transmission, research magnets and other applications.

Where: **National MagLab/Applied Superconductivity Center**

3 MEMORY FOR THE INTERNET OF THINGS

Scientists are studying compounds that can be controlled by magnetic and electric fields, making them promising for use in a novel kind of computer memory (called resistive random-access memory, or RRAM) that uses less power than existing systems. Such compounds could be used for memory in the rapidly growing "internet of things," for everything from smart cars to smart coffee makers.

Where: **Institute for Solid State Physics, Tokyo**

4 CLEANER WATER

Scientists found that stormwater runoff and stormwater pond outflow contained ecologically reactive nitrogen that, when transported downstream, may contribute to nutrient pollution and harmful algal blooms.

Where: **National MagLab/Ion Cyclotron Resonance**

5 HEALTHIER PREGNANCIES

Using the world's most powerful MRI machine, researchers are studying how mothers transfer glucose to their fetuses, work they hope will improve treatment for preeclampsia and for gestational diabetes, which affects 7 percent of pregnancies.

Where: **National MagLab/Nuclear Magnetic Resonance**

6 MORE EFFICIENT A/C

Ongoing research on the magnetocaloric effect – how magnetic fields can change the temperature of some materials – could lead to new kinds of air conditioners and fridges based on magnetic refrigeration, which is more efficient than gas compression.

Where: **Institute for Solid State Physics, Tokyo**

7 COMBATING CANCER

With strong magnets as their weapons, researchers fight cancer on numerous fronts, including pioneering a novel MRI technique to track chemotherapy's effects on brain tumors; identifying biomarkers for breast cancer; and developing better MRI contrast agents for diagnosing early-stage cancer.

Where: **National MagLab/Nuclear Magnetic Resonance & Ion Cyclotron Resonance**

8 BETTER BATTERIES

Scientists are developing safer lithium-ion batteries with more capacity, working toward solid electrolytes that could replace potentially unstable solutions.

Where: **National MagLab/Nuclear Magnetic Resonance**

9 FASTER COMPUTERS

Researchers are working to improve the performance of qubits (the building blocks of the quantum computers of the future) by reducing interference from the environment.

Where: **National MagLab/Electron Magnetic Resonance**

FROM THE LAB TO THE LIVING ROOM

How do the kinds of science innovations illustrated here make it from the laboratory into your life? To find out, *fields* magazine talked to Lawrence Tinker, a chemist and entrepreneur-in-residence at the Florida Institute for the Commercialization of Public Research, a not-for-profit organization funded by the state of Florida to help startup companies licensing technologies from universities and other institutions in the state.

Q What are some of the biggest pitfalls scientists face when trying to commercialize a discovery?

A Believing that your technology is something that somebody wants. It happens a lot, that an inventor or scientist believes that their technology is the greatest thing. But then they get out in the real world.

Q What does it take for a scientist to be a successful entrepreneur?

A An understanding of how business operates, an understanding of things beyond the academic world that they're in, because it's very different. (They need) an ability to look at the big picture and not focus on the science, but on the business side of things: How can I do this in a way that's attractive to somebody so that they want this product?

But I'll have to say that scientists typically aren't good entrepreneurs. They get too married to their technology and they don't really look at it from an arms-length standpoint and ask, "Does anybody care about this?"

Q What are the opportunities like for scientist-entrepreneurs today?

A They are better today than they were 10 or 20 years ago. (Years ago,) there were a lot of large companies that had a lot of research facilities. It's not like that so much anymore. The business model has changed where larger companies look for smaller technologies. There is more opportunity for the small guy to make it by being recognized by the large companies.

Q What are some of the biggest hurdles science entrepreneurs face?

A One thing that can be especially difficult for new entrepreneurs is not realizing that they have to constantly be raising money. They focus too much on the science and technology instead of focusing on the fact that they need to raise money. And they end up running out of money.

Q What advice would you give a prospective science entrepreneur?

A Find a good, experienced entrepreneur to start the company. Be involved in it, but don't try to do it on your own. That's the first thing I would tell them.

Q So they need to consider what role they want to play?

A If you want to be a startup, you need to be willing to quit your day job. If you don't, it will be difficult to make something happen.

Q What other advice would you give?

A Don't be unwilling to look at alternative ways to do what you're trying to do. In other words, if you have a technology that you develop and you believe it should go in this market, be willing to look at the possibility that there is a better application in another market.

Q What's a cautionary tale from your own experience?

A Be sure you understand there is a need for your technology in the market. Do everything you can to understand that. If you don't understand it, you're going to end up at a place where you have a product and nobody wants it. Be willing to pivot to something else quickly and pursue that technology.

Q What makes a good pitch?

A Most investors, while they are interested in the technology, don't really want to know all the technical details. They want to know: What are the things you need to do to get this to a commercial product? What's the timeline for doing it? How much money do you need to do it? What are your projected financials? And how am I going to make money at this?

WEAVING A SCIENCE WEB

FOR GREAT RESEARCH TO SPREAD THROUGH THE WORLD, IT TAKES A LATTICE.

At the end of the day, science is all about sharing: sharing ideas, discoveries, techniques, successes and failures. After all, exciting insights or results aren't worth the bits used to record them if they never make it off a researcher's hard drive.

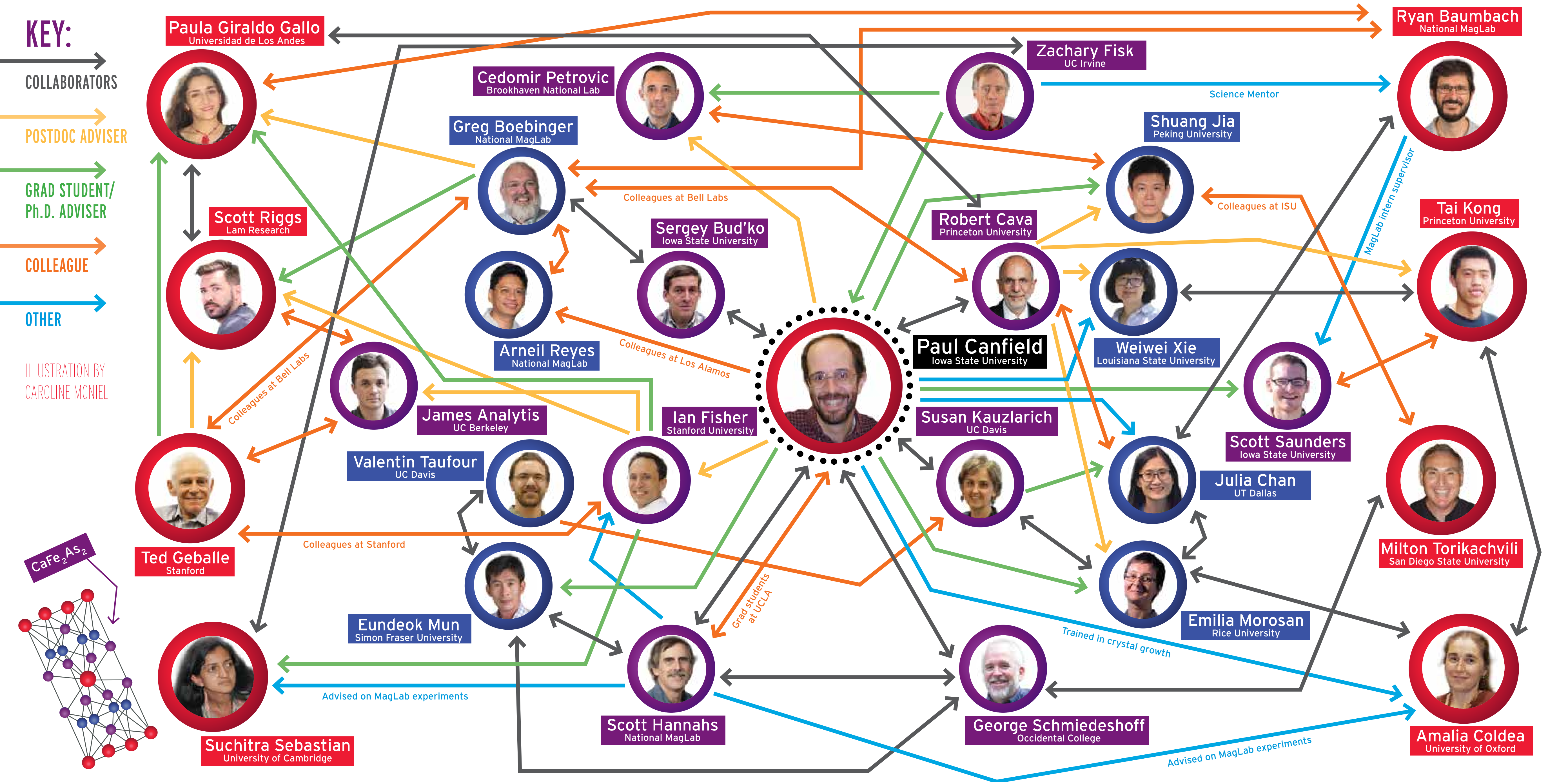
Paul Canfield, a physicist at Ames Laboratory and Iowa State University for more than two decades, knows that as well as anyone.

Canfield researches the design, discovery, growth and characterization of novel electronic and magnetic materials, and has made key contributions to our understanding of superconductivity, heavy fermions, quantum criticality and other phenomena. Over the course of his career, he has crossed paths with thousands of fellow scientists by co-authoring papers, mentoring students, and traveling the world to train others on his techniques. Science must be social, he said: That's how ideas spread, disciplines cross-fertilize and transformative science happens.

"My feeling is, at a certain point, you're much better served working with people who a) might be able to bring different or new takes and ideas, or b) are experts at what they do," Canfield said. "To understand the many aspects and facets of a new material, you need to appreciate it holistically."

This high-impact scientist sits at the center of a complex web of physicists and chemists spanning generations and continents, each entangled in his or her own professional network. The many overlapping relationships are far too complex to represent in any diagram. Nevertheless, we have taken a modest stab at doing just that on this page, using one of Canfield's well-studied crystals, calcium iron arsenide ($CaFe_2As_2$), as the lattice structure for this "web of science." Though far from exhaustive, it at least gives a sense of the very collaborative nature of science. – *KC*

For details on the scientists featured here, visit **fieldsmagazine.org**



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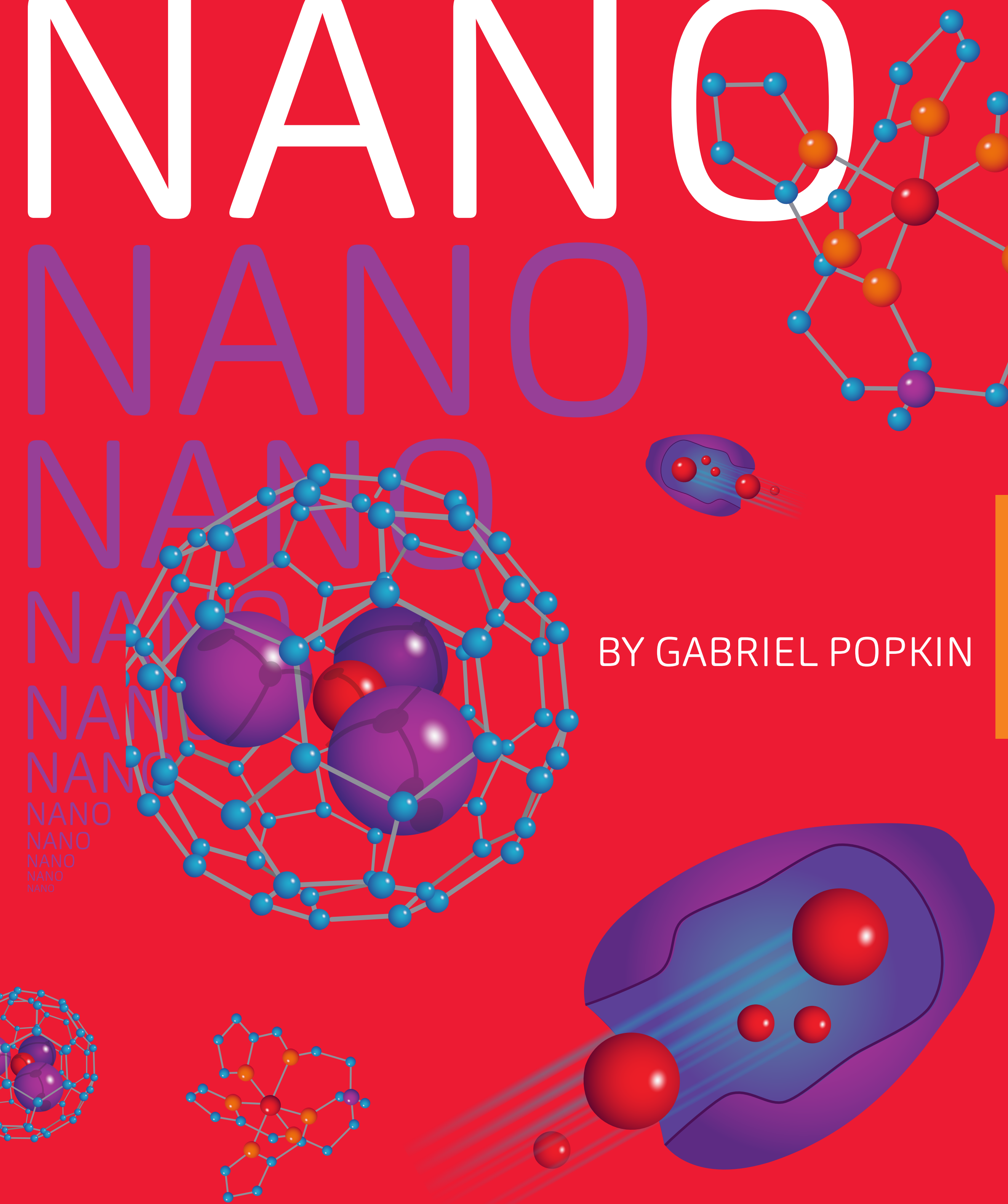


BY GABRIEL POPKIN

From nanorockets to nanocages, good science can come in tiny packages — all with the aim of solving really big problems.

In 1959, the famous physicist Richard Feynman gave a talk titled "There's Plenty of Room at the Bottom." Feynman's message to his peers was that the nano-world — the creation and control of matter at the scale of billionths of a meter — had barely been explored.

More than 50 years later, nanoscience has exploded. Universities around the world have launched nanoscience centers and initiatives; the United States funds a National Nanotechnology Initiative to the tune of more than $1 billion a year. More than 1,600 nanotechnology-based consumer products have hit the market, from high-tech coatings and sunscreens to catalysts and artificial tissue components.

And yet, a talk with Feynman's title would still be apt. In fields from electronics to data storage to medicine, many scientists feel that nanotechnology's potential is only starting to be realized.

"It's a vast field, and there's still new basic research coming out," said Vivien Zapf, a physicist at the National High Magnetic Field Laboratory. "Especially the ability to sense and manipulate individual atoms is a whole other field."

Scientists haven't always had the tools to study small-scale matter with the required precision. Ironically, studying the world's smallest constituents often requires some of the largest and most sophisticated hardware. (Just think of the 27-kilometer, $10-billion Large Hadron Collider needed to discover the subatomic Higgs boson.)

The same is true for nanoscience. Some of the field's most cutting-edge work is now being done in high magnetic field labs around the world, where clever uses of the world's strongest magnetic fields are teasing out microscopic matter's secrets.

Nanocages may hold key to advances in health, energy

In 1985, chemist Harry Kroto and colleagues at Rice University in Houston zapped a pile of graphite with a laser and discovered a strange new molecule. It consisted of 60 carbon atoms arranged in a pattern similar to that of a soccer ball.

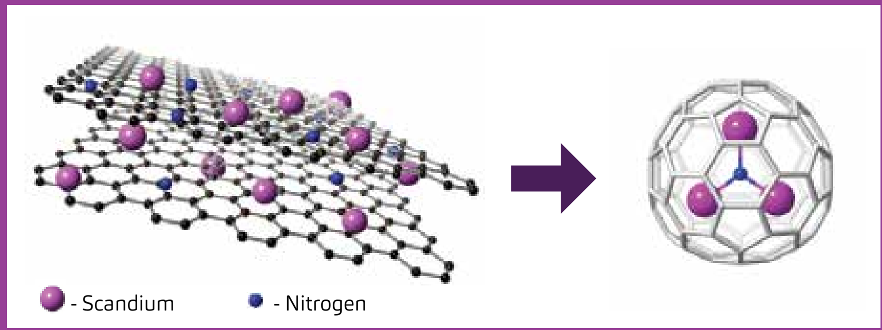
They named their new material buckminsterfullerene, after the geodesic domes of visionary architect Buckminster Fuller; others gave it the catchier term "buckyballs."

The discovery inspired an avalanche of research into the molecule's unique mechanical and electrical properties, and netted its discoverers the 1996 Nobel Prize in Chemistry.

Today, Paul Dunk, a chemist at the National MagLab in Tallahassee, Florida, who worked with Kroto until his death in 2016, is helping to make these properties useful. He's not studying C_{60}, but other strange and wondrous forms that appear when he zaps graphite, metals and other elements with a laser.

Hints of the field's potential appeared as early as 1999, when scientists unexpectedly found carbon molecules made up of 80 atoms, rather than 60. Like C_{60}, C_{80} was stable, robust and symmetrical. But these larger buckyballs held a surprise. Inside each molecule's walls were three atoms of a metal called scandium and a nitrogen atom. C_{80} could, as it turned out, encapsulate other atoms.

Image credits: (Left) Stephen Bilenky. (Right) Paul Dunk.



(Left) Paul Dunk. (Right) Dunk's research has illuminated how carbon nanocages form when graphite, a metal and nitrogen are vaporized with a laser.

The discovery of these "nanocages" opened up the possibility of using buckyballs to transport tiny cargoes. Gadolinium, for example, is an excellent contrast agent for the magnetic resonance imaging (MRI) technology often used in medicine, but it is also toxic. Gadolinium in a nanocage, however, could safely travel through the body to a site where it's needed.

But there is a holdup: No one understands the violent, chaotic reactions that bring these nanocages into being, much less how to manufacture them consistently and cheaply.

Dunk and collaborators in Texas and Spain are trying to change that. They vaporize concoctions of graphite mixed with different metals and other elements, and study the resulting nanocages in an ion cyclotron resonance mass spectrometer, a device built around a powerful magnet that weighs molecules. In this machine, each molecule circulates at a slightly different frequency that depends on its mass and electric charge. Dunk and his colleagues have used the device to study virtually all the elements in the periodic table to show which metallic atoms can take up residence inside fullerenes.

> "There are a lot of new structures that have unique properties that have not been found. We hope to accelerate that process."

"The variety is staggering," he said.

The difference between the frequencies in mass spectrometry becomes more pronounced as the magnetic field strength increases, so the National MagLab's world-record instruments help Dunk separate and identify the vast diversity of molecules he produces in the lab.

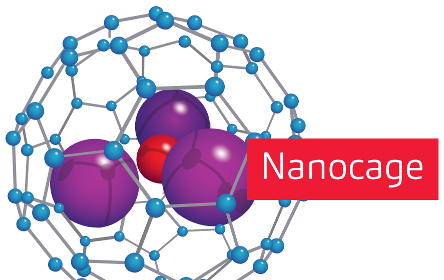
"With other mass spectrometry methods that don't use high magnetic fields, you can't get that ultra-high resolution, so most of these nanocages have been basically invisible and undetectable," Dunk said. "That high magnetic field allows us to probe many self-assembly processes for the first time, and to develop new nanocages. It fills a really huge gap in nanoscience."

Beyond creating new metallofullerenes, Dunk and his colleagues test theories of how these compounds form by looking for hypothesized intermediate molecules between the original reactants and end products. They have shown that, unlike what many scientists believed, the cages do not shrink from or break off of larger globs of carbon, but rather nucleate around the metal, carbon atom by carbon atom. A paper they have written describing the process is slated for publication later this year.

With this improved understanding, the researchers hope to pave the way toward more controllable and efficient methods for manufacturing cluster nanocages for technologies ranging from new light-based electronics (or photovoltaics) to molecular electronics.

"There are a lot of new structures that have unique properties that have not been found," Dunk said. "We hope to accelerate that process."

Added Dunk, "If (cluster nanocages) can be formed in sufficient quantity at the right price, the applications that tackle human health and energy concerns could become an immediate reality."



(Right) Electron microscope images of vesicles. In the images on the left, they are outside a magnetic field and have only a small opening. In the images on the right, taken in a 20-tesla magnetic field, the vesicles are deformed, resulting in a large opening.

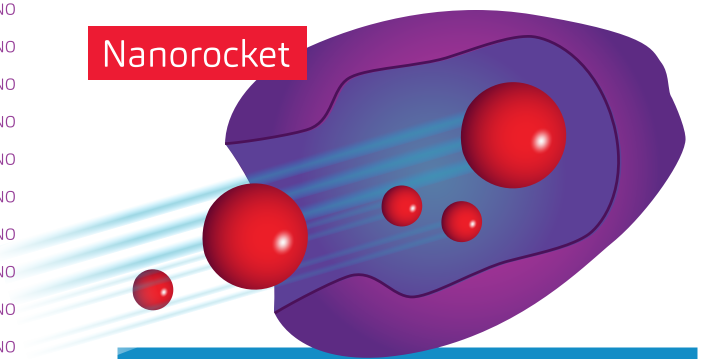
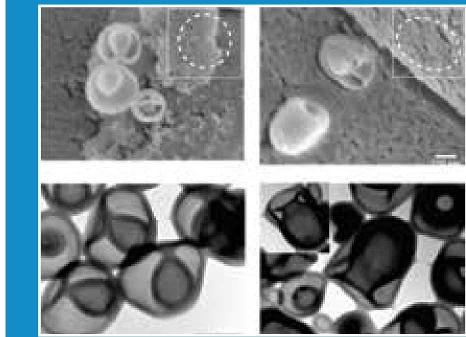


Image credit: Radboud University.



Drug delivery is rocket science

Think of it as door-to-door drug delivery — on the cellular level.

Peter Christianen, a physicist at the High Magnetic Field Laboratory in Nijmegen, the Netherlands, envisions a day when tiny rockets, careening through a patient's veins, will dispatch medicine directly to the site where it's needed.

Technically, the "rockets" are stomatocytes, artificial cells with mouth-like openings. Similar to a cell or vesicle in your body, stomatocytes have membranes consisting of long carbon chains, each with a water-seeking and a water-repelling end. These chains, pressed against each other, form a water-tight boundary that divides inside from out.

Recent research in this area by Christianen and his collaborators is a good example of how serendipity can lead scientific discovery into unexpected, but very promising, directions.

A few years ago, some of Christianen's colleagues placed platinum and hydrogen peroxide into a tiny stomatocyte. They found that the chemical reaction that ensued — the liquid peroxide "fuel" split into water and oxygen gas that blasted out of the cell — made the vesicle into a tiny rocket.

Christianen and his team suspected that they could use magnetic fields to reshape and steer the "nanorockets." But when placed in a strong, 20-tesla magnet, the stomatocytes didn't deform much.

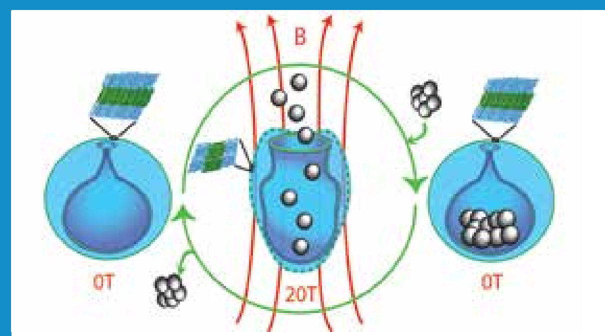
> "We thought, 'OK, we can use it as a capture-and-release device for drug delivery.' It's totally reproducible and reversible."

However, the magnetic field did cause one crucial change: The vesicles' mouths opened. Immediately the team had a new idea: Stomatocytes could be loaded with drugs, shuttled to specified sites in the body, and zapped with a magnetic field to force them to disgorge the drugs. The scientists dubbed them magneto-valves.

"We thought, 'OK, we can use it as a capture-and-release device for drug delivery,'" Christianen said. "It's totally reproducible and reversible."

Developing nanorockets turned out to be just a first step. The next was learning how to mold them, a process that also involved some science serendipity.

Image credits: (Left) Peter Albers (Right) Radboud University.



(Left) Peter Christianen. (Right) The vesicle begins, without any magnetic field, closed. Then, after a magnetic field is applied, the mouth opens. Finally, after the cargo is loaded and the field is switched off, the filled capsule closes. When a magnetic field is reapplied (not shown), the vesicle will open and release its cargo.

Christianen learned that osmotic pressure (determined by the concentrations of organic solvents inside and outside the vesicles) influences a vesicle's shape. So he and his colleagues tried a new experiment. First, they added water to a mixture of long carbon chains that had been dissolved in an organic solvent; the chains formed spherical vesicles. Then the researchers changed the osmotic pressure by diluting the solvent outside the vesicles; they responded by buckling into various shapes, each suggesting different applications.

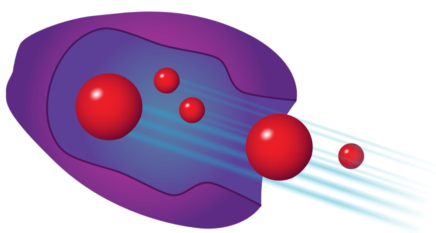
Disc-like structures may have different flow properties or be better for cell-adhesion, said Christianen, while spherical vesicles could be used as nanoreactors for chemical reactions, and stomatocytes as drug delivery vehicles.

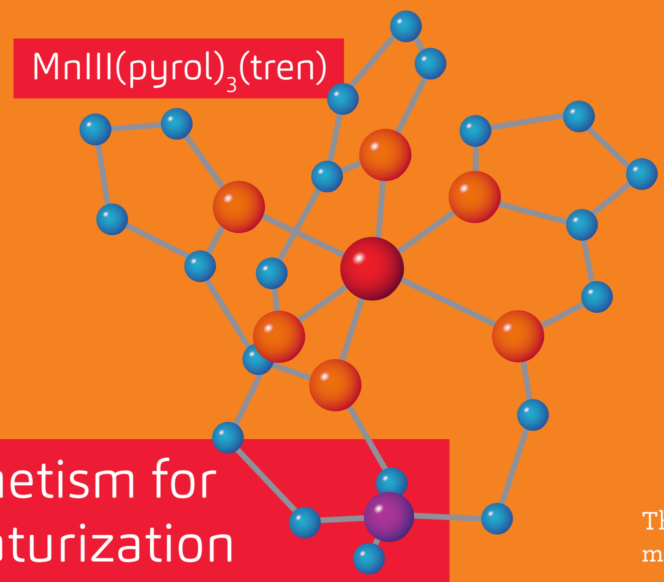
"So different shapes give different functionalities," he said.

Then Christianen's team turned again to magnetic fields — this time to determine exactly what shapes they were creating. They employed a technique called magnetic birefringence, which uses polarized laser light to image how objects are oriented in a magnetic field. This allowed them to precisely map how vesicles' shapes change as osmotic pressure changes.

This measurement and control of stomatocyte nanorockets brings Christianen's team a step closer to one of medicine's holy grails: precision drug delivery. The technique is especially promising because it would require nothing fancier than a run-of-the-mill MRI machine.

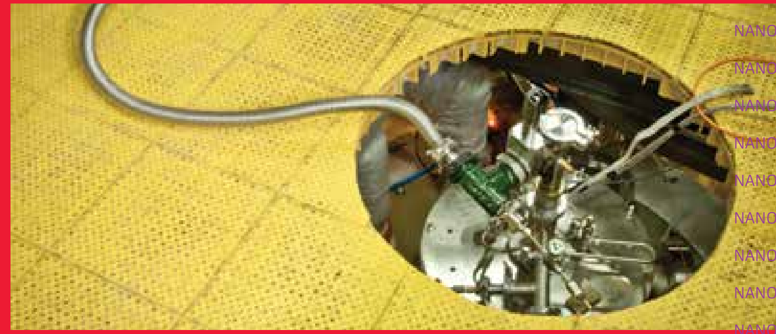
With more hard work — and perhaps a dash more serendipity — that vision seems bound to come to pass.





Magnetism for miniaturization

Image credits: (Left) Richard Sandberg (Right) Dave Barfield



(Left) Vivien Zapf. (Right) Zapf's research was conducted in this world-record 100-tesla pulsed field magnet.

Miniaturization isn't just happening in medicine. In physics, researchers are probing different kinds of molecules for properties that will lead to the next generation of electronics, even quantum computers.

In the hot field of spintronics, for example, scientists are looking for ways to use the "spin state" of electrons (or whether an electron is oriented up or down) as the ones and zeros of binary code.

At the National MagLab's Pulsed Field Facility, physicist Vivien Zapf is leading a team down a different path to nano-level electronics: multiferroics.

In multiferroic materials, one behavior can be used to control another, akin to the way electricity can generate magnetism and vice versa. But in multiferroics, that coupling is between magnetism and something called ferroelectricity. And just as magnetism and electricity help make the modern world go round, so too, some physicists believe, will the pairing of magnetism and ferroelectricity help the world of the future go round.

In ferroelectric molecules, the distribution of electric charge is uneven — one side is more positive, the other more negative. If you apply an electric field to it, you can get that polarity to flip. So ferroelectricity is a way of moving electric charges around, and in that sense is like electricity. However, ferroelectricity is a lot greener.

"Unlike spintronics, you're using voltages instead of electric current, so you reduce the power consumption," Zapf said.

That means ferroelectricity, when paired with magnetism in multiferroics, could pave the way to smaller, more powerful electronic devices that are far more energy-efficient than could be achieved with spintronics.

To that end, Zapf and her collaborators, including National MagLab physicist Shalinee Chikara, try to create multiferroic molecules. They believe they have found a promising candidate: a molecular magnet featuring a manganese atom surrounded by rings containing carbon and nitrogen — or MnIII(pyrol)$_3$(tren), if you want to get technical.

By putting the molecule in very high magnetic fields up to 65 teslas, the scientists cause the electron spins to transition to a different state.

> "By letting physics and chemistry intersect, we get access to this new way of approaching multiferroics."

It's a new way to pursue multiferroics.

"Instead of thinking about which way the spins are pointing, you actually change their size," Zapf said. "Which means you're changing the configuration of electrons within one atom so that, overall, the atom ends up with a different degree of magnetism than it had before." That change in magnetism triggers the ferroelectricity, making the material multiferroic.

There's something else special about Zapf's molecule: While the majority of work in multiferroics has focused on inorganic materials (they don't contain carbon), Zapf's group is one of a few that studies materials with organic molecules, which do contain carbon. Their success opens up hundreds of thousands of similar organic materials for previously unexplored multiferroic effects, Zapf said.

"That has us pretty excited," Zapf said. "These hybrid inorganic-organic materials are a new route to designing magnetism."

Zapf may never have pursued this promising line of research if she hadn't decided to venture outside her discipline and attend a chemistry conference a few years ago. There, she learned about spin state transitions — an area most physicists don't know much about.

"By letting physics and chemistry intersect, we get access to this new way of approaching multiferroics," Zapf said.

With her chemist colleagues from around the world, Zapf is cracking the door on a host of possible applications. Multiferroics could lead to new, highly sensitive magnetic sensors and new designs for small-scale, high-frequency devices such as antennas, power transformers or MRI magnets.

But figuring that out is someone else's job, she said.

"There are people who specialize in applications. I'm more into, 'Let's design crazy new ways to make ferroelectrics talk to ferromagnets,'" she said. "I'm one of the people who feeds them the new ideas and new approaches."

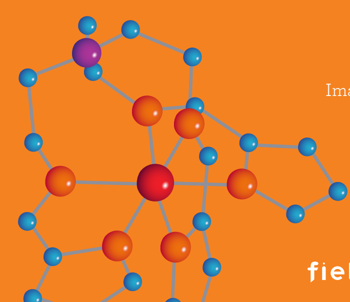


Image Credit: Vivien Zapf and Shalinee Chikara

SLOW TRAIN TO SCIENCE

SEX AND THE SPINELESS

Roundworms are pretty small. If you took one particular species, *Caenorhabditis elegans*, and lined them up mouth to anus along the bottom of this page, you'd have an invertebrate parade about 184 organisms long. They reproduce quickly, don't eat much and are pretty quiet, which are reasons they make great model organisms for scientists to study.

Chemist Rebecca Butcher spends a lot of time in the company of worms at her University of Florida laboratory. Among other things, she studies the pheromones they secrete in order to communicate with each other. In a project involving high magnetic fields, Butcher and her group studied pheromones that roundworms emit when their numbers surge, and which cause the worms to change to a state called the dauer larval stage.

Butcher explains: "They realize, 'Oh, our population density is really high, we're going to run out of food! We'd better enter this dauer larval stage. That will allow us to survive this period where there are too many worms and too little food.'"

Sound intriguing? Hop on this Slow Train to Science, and we'll take you on the journey of this research project and explain why those of us with backbones should care. (You could also try taking this trip by wormhole, but we can't guarantee your safe return.) *-K.C.*

REBECCA BUTCHER

HOP ON HERE!

1 WHIP UP SOME WORMS.

To study the pheromone produced by the roundworm, Butcher first has to breed a batch of the little critters.

HOW DO YOU MAKE THEM MULTIPLY?

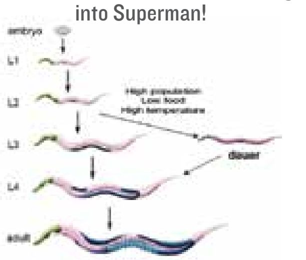
Take some worms, put them in a culture flask with a medium (some salt, cholesterol) and add their favorite food, bacteria. Shake well — then crank up the Barry White!

THEN WHAT HAPPENS?

They eat, develop, reproduce, and repeat. After a week or so, you have exponentially more worms than you started with.

2 WATCH FOR DAUER POWER.

The worm boom will reach a tipping point at which the amount of dauer pheromone in the environment triggers the worms' morphing super-power: They turn into dauer larvae — kind of like Clark Kent transforming into Superman!



3 HARVEST MOLECULES.

Butcher collects the medium, removing all the worms. The population-controlling pheromones secreted by the worms are in there, but so is a lot of other stuff she doesn't need. To get rid of it, she follows a sequence of filtering steps.

FIRST, LYOPHILIZE IT.

That just means to freeze-dry it. That removes the water and leaves you with the "crusty stuff," as Butcher puts it: a mix of organic molecules and salts.

ORGANICS ONLY.

Butcher eliminates inorganic molecules (salts, etc.) that are not of interest until all that's left is a crude organic extract.

Organic molecules are associated with living things and contain carbon.

4 A MUDDLE OF MOLECULES.

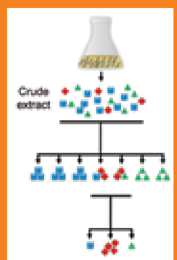
That extract is like a haystack, full of hundreds of thousands of molecules, including glucose, amino acids and other miscellaneous stuff left over from the bacteria and worms. In that mix, Butcher still needs to pinpoint the pheromones — the needles in that haystack.

5 SORT IT OUT.

Butcher sorts her molecules like M&Ms separated into color groups, using activity-guided fractionation.

FRACTIONATION?

That means dividing the molecules that make up the organic extract into piles based on their size, polarity (how positive and negative charges are distributed) or other properties.



6 PILE TRIALS.

Butcher assays each fraction for biological activity.

FILTER OUT IMPOSTERS.

Say Butcher ended up with 30 different fractions – 30 different types of molecules. Most don't contain the pheromone she's looking for. So she tests each pile by taking some of those molecules, exposing the worms to them, and watching what happens. If the eggs laid by those worms develop into adults: Sorry! Play again! If they turn into dauer larvae: Bingo! You've found the pheromone.

7 LIST OF INGREDIENTS.

Once the extract is pure, it's time to map its molecular makeup. This is where magnets come into the picture.

WEIGH IN.

Butcher identifies the constituent parts of her target molecule with a mass spectrometer.

SUM OF ITS PARTS.

Powered by a magnet, the mass spectrometer weighs the molecule. The process identifies not only which atoms are in the sample (oxygen, hydrogen, etc.), but how many there are of each. The instrument can differentiate among the atoms because each has a unique molecular mass.

8 ASSEMBLY REQUIRED.

Using nuclear magnetic resonance (NMR) spectroscopy, Butcher then tries to figure out how Mother Nature assembles all those parts she just identified.

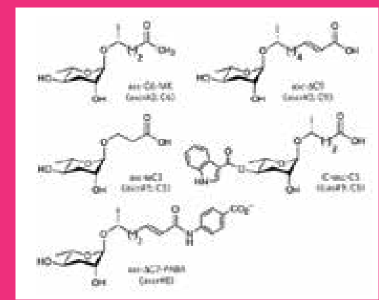
MAP IT OUT.

In NMR, scientists use radio waves and magnets to map out the atoms in a molecule. Just as each atom has a unique weight, it also has a unique resonance frequency. So using a specific frequency, Butcher finds the oxygen in a molecule; another frequency helps her find carbon, etc. The techniques can get pretty advanced: Heteronuclear multiple bond correlation (HMBC) NMR, for example, reveals which hydrogens in the molecule are two to three bonds away from carbons. "It's like a puzzle," said Butcher. "We'll get pieces of information and then we have to come up with a model for how we think the molecule will look."

9 DRAW THE MODEL.

Using the data from the NMR experiments, Butcher comes up with an image of what the dauer pheromone looks like.

The dauer pheromone is actually a set of five different chemicals that work together. When the worms secrete all five and sense them from one another, this triggers their transformation to the dauer larval state.



10 SYNTHESIZE.

Butcher makes the molecule from scratch in the lab.

11 TEST THE MOLECULE.

Butcher exposes her homemade molecules to some worms to see if they trigger the dauer larval state. If they do, that's a good sign.

She then makes sure the NMR spectra of the synthetic material match those of the natural compound. If so, it's official: Her model structure is correct.

NMR spectra include information on the molecules' makeup and structure.

TERMINUS

12 PLAN MORE RESEARCH!

Knowing the structure of these and similar molecules allows scientists to pursue new research questions.

How does this research help us understand analogous processes in other organisms, including humans?

How can scientists use what they know about worms to control their populations or behaviors?

What about other roundworm species? What pheromones and hormones do they produce?

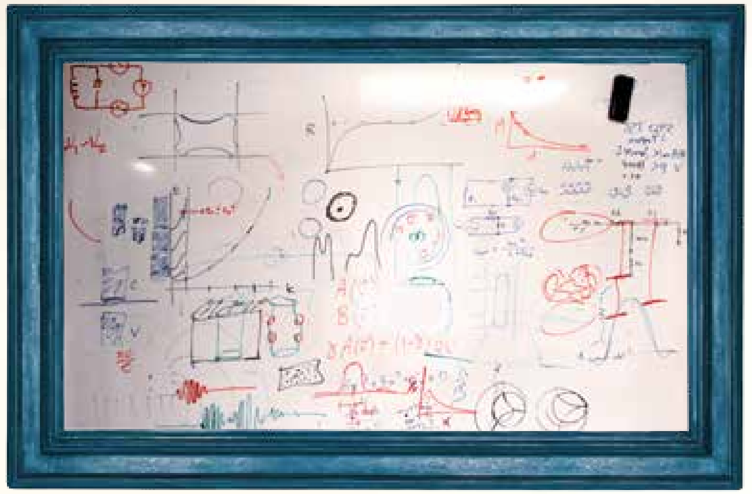
How do worms biosynthesize these molecules?

How do the molecules function in the worm?

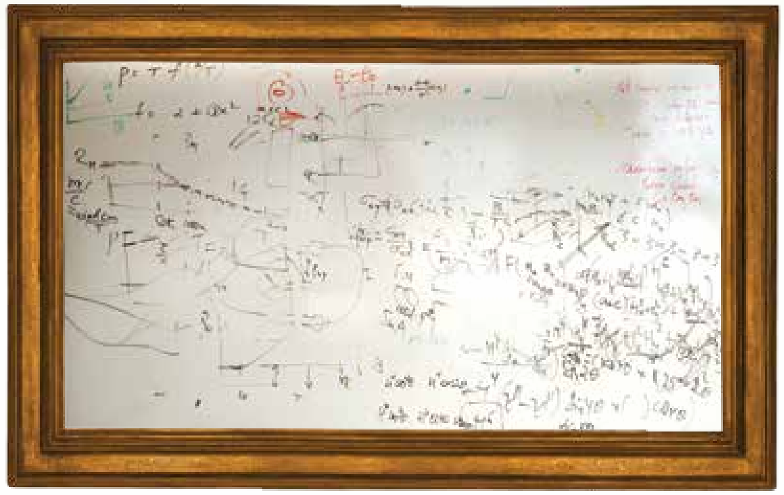
Which neural receptors do they target in the worm's brain?

There are tens of thousands of different species of roundworms (or nematodes) on the planet, many of which are parasitic.

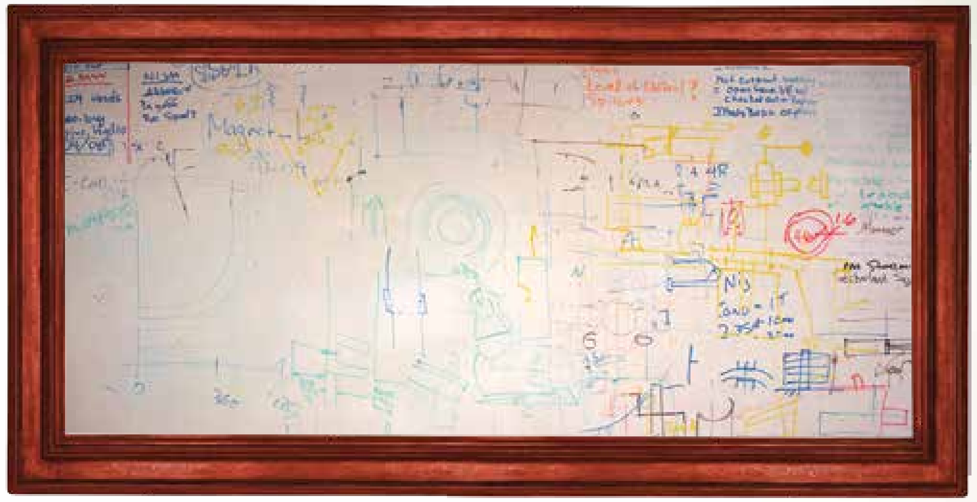
Whiteboard as Canvas



William Coniglio
Scratchpad
Marker on Whiteboard



Arkady Shekhter
Scientist at Work
Marker on Whiteboard



Scott Bole
Mayhem
Marker on Whiteboard

The eyes of an artist reveal the beauty and emotion behind this quintessentially scientific medium.

The pursuits of science and art have a lot in common, as was amply in evidence one day last summer when sculptor Carolyn Henne visited the National High Magnetic Field Laboratory. For that afternoon, it became the National High Magnetic Field Museum.

While touring the lab's unique instruments and facilities, the Florida State University art professor also viewed a kind of "found art" hidden in plain view. On whiteboards depicting the collaborative, creative work of science, Henne saw works of art. Studying them with an artist's sensibility, she saw echoes of modern masters, including the layering of Nancy Spero, the cryptic markings of Cy Twombly and the symbolism of Elizabeth Murray.

The whiteboard is indeed the scientist's canvas, a place to collaborate and create, to sketch diagrams, equations and graphs using the Fauvist reds, greens, blues and yellows available in his pack of markers.

It doesn't matter, said Henne, that she might not know the intent behind those bold scribbles; that's often the case in abstract expressionism and other modern and contemporary styles of art.

"But there's enough there to allow you to engage, because you know these things have information embedded in them," Henne said. "Now, whether or not I can pull that particular information out, probably that will never happen. But I can be interested in it in a more visual way."

Like many museum masterpieces, observed Henne, the whiteboards display the "mark making" artists use to work through issues and communicate that process to others.

"Mark making is all designed to move yourself closer to some sort of solved problem or answer to a question," Henne said. "Scientists do that and artists do that. … It can be done with a brush, it can be done sculpturally, it can be etched into metal, or (it can be) this kind of mark making, which is just reflecting and communicating thought and moving through an idea."

Scientists use other tools to record ideas: lab notebooks, image processing software and, of course, PowerPoint. Still, there is something unique about the scale, physicality and erasability of a whiteboard. It invites collaboration and expands thinking in ways pages and computer screens can't.

"It's faster and it's bigger and it's easier to be animated," noted National MagLab physicist William Coniglio, one of the artist-scientists Henne spoke with on her visit.

Here's a small sampling of the whiteboard collection currently housed at the MagLab museum. *-K.C.*

Scratchpad

If the whiteboard in the office of William Coniglio could talk, it would be deafening.

"There are 20 discussions on this board," he said.

Coniglio reserves the reflective, white rectangle that fills one office wall for teaching. As to its composition, he said, conversations with tall students are on top, and those with shorter students are on the bottom. Overlapping reds and greens and blues, each color a new conversation, are like partygoers yelling to be heard above the din.

He has long since given up trying to erase the obstinate older markings.

"You just pick a complementary color and just go right over top of it," Coniglio said. And he dismissed the scribbles as science ephemera: The really good stuff ends up in his lab notebook, he said.

Pointing to a vase-like green and red shape, Henne asked if it represented an object being connected to another. In fact, Coniglio explained, it depicted a Fermi surface, an arcane physics concept. But as with any work of art, Henne did not need to know such details in order to appreciate the work through her own filters.

"It's probably more interesting for me to come up with all my own explanations for what I'm seeing on here as opposed to you telling me what it really is," she told Coniglio. "And I think that's true when artists finish a work and it goes out in the world."

Scientist at Work

At this whiteboard, Henne's eyes were instantly drawn to the overlapping, monochromatic formulas scrawled in the lower right corner. On top of them, repeating diagonal lines looked to have been added by a vehement hand.

"Compositionally this is the focal area, because it's the busiest and most interesting in terms of worked surface," she said.

That artist then entered the room. With a quiet intensity, physicist Arkady Shekhter picked up a black marker and, adding to the ruckus of swirls and angles, explained the science behind those markings. Although he quickly ascended to abstruse levels, his fervor, at least, was plain. As he sketched and talked, Henne thought of Swiss artist Alberto Giacometti, known for working his drawings so energetically he would cut right through the paper.

"There's a compulsion to go over it — get it right, get it right — and I was seeing that in some of the things that he was doing," Henne later observed.

Both whiteboards and (Shekhter's preference) chalkboards play a critical role in the scientific process, he said. As a theorist, he spends a lot of time thinking. But eventually he has to present that thinking to others, and that's where the board comes in.

"Sometimes you realize it's complete nonsense; sometimes it makes you think about something else," Shekhter said. "It's very important just to verbalize it, and to verbalize it in front of other people."

Mayhem

The office of magnet engineer Scott Bole is home to many artsy artifacts, including fake bills dangling from ceiling tiles, a retired magnet part revamped into a lava lamp and, of course, an expansive whiteboard covered with ideas, to-do lists, graphs and magnet designs. To Henne, it brought to mind the term palimpsest, which refers to a reused writing surface that bears the traces of earlier markings. Artist Jean-Michel Basquiat was known to use his canvases like palimpsests. Whether purposefully or not, Bole does the same. Featuring the smudges of half-hearted erasures, his whiteboard, Henne noted, was like "a depiction of time."

"So there was removal, but there was still evidence of what had been there before," she said. "As a sculptor, I'm really attracted to that idea. But also, in a lot of drawings and paintings, there's evidence of what was there before."

Read more about Henne's insights into the overlapping worlds of science and art and view other whiteboard masterpieces at **fieldsmagazine.org**.

Have your own chef d'oeuvre? Share it with us on social media **@nationalmaglab**.

Image credits: Stephen Bilenky

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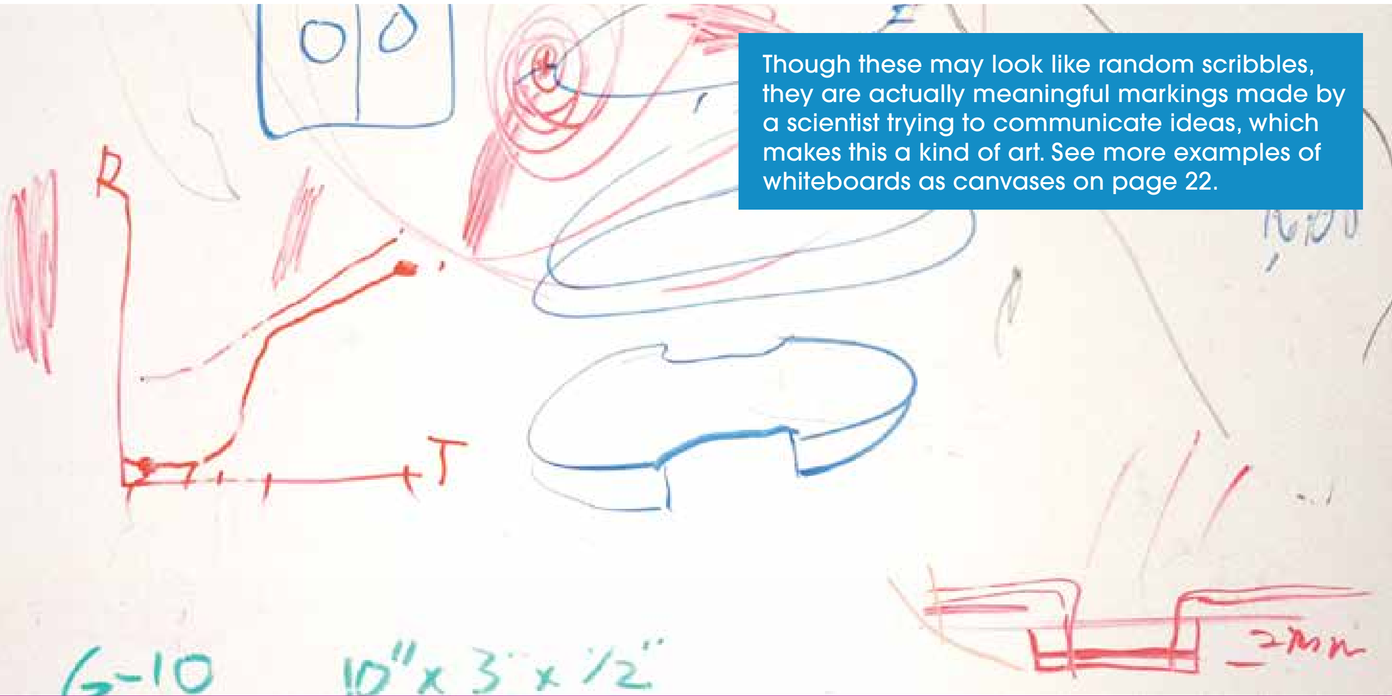

Though these may look like random scribbles, they are actually meaningful markings made by a scientist trying to communicate ideas, which makes this a kind of art. See more examples of whiteboards as canvases on page 22.

NATIONAL MAGLAB

Headquartered in Tallahassee, Florida, The National High Magnetic Field Laboratory is home to some of the world's strongest and most unique magnets, and belongs to a network of high-field magnet labs around the world offering scientists cutting-edge instruments for their discoveries.

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