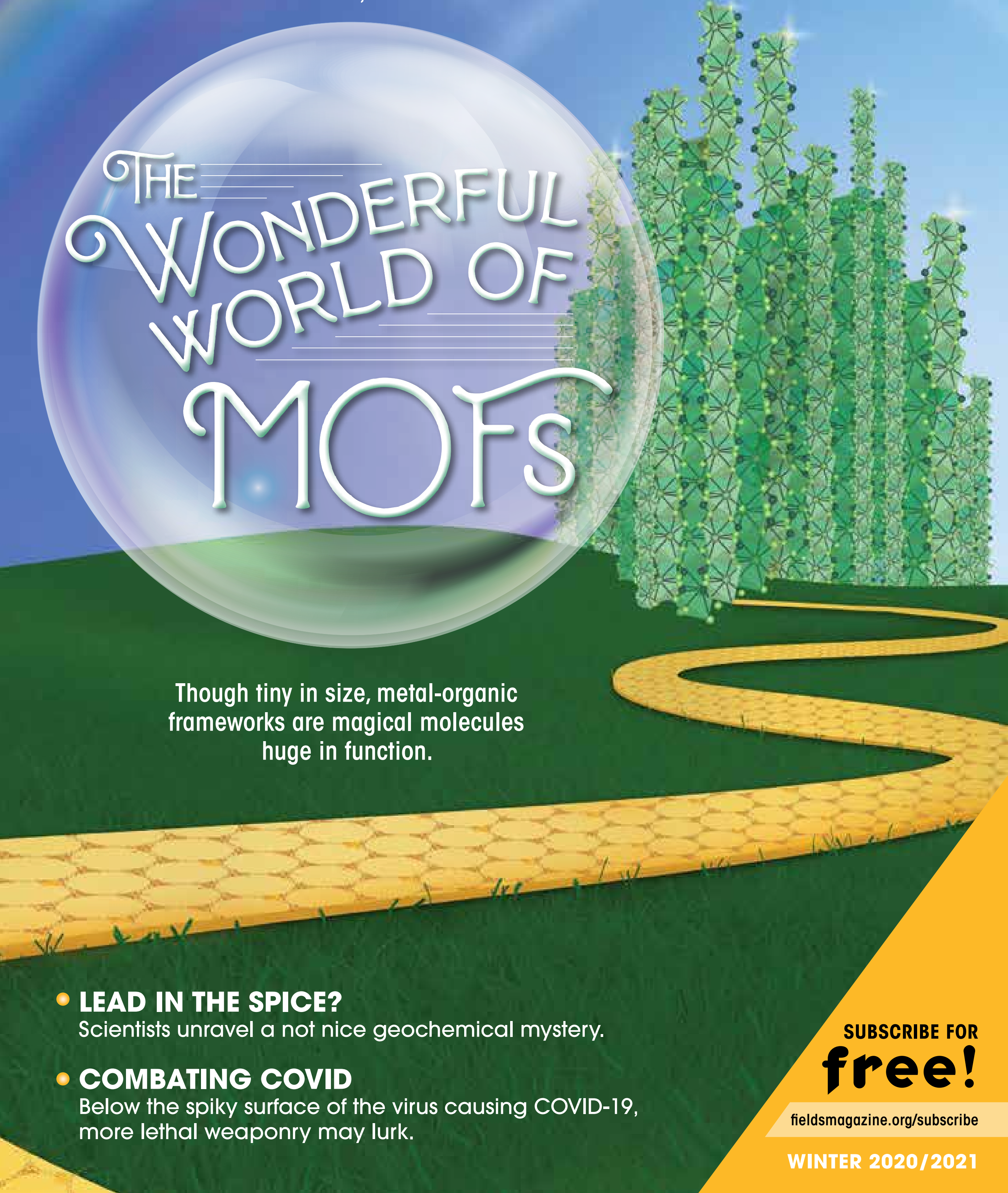
fields

SCIENCE, DISCOVERY & MAGNETISM



The Wonderful World of MOFs

Though tiny in size, metal-organic frameworks are magical molecules huge in function.

- **LEAD IN THE SPICE?**
  Scientists unravel a not nice geochemical mystery.
- **COMBATING COVID**
  Below the spiky surface of the virus causing COVID-19, more lethal weaponry may lurk.

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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 LINES

Quick hits on the diverse discoveries powered by high-field magnets.

An Attractive Way to Recycle

The world is awash in plastic. Hundreds of tons of the stuff is produced every year worldwide, most of which never makes it to a recycling center.

Part of the reason why is that plastic is cheap to produce. In order to make recycling it more attractive, the process needs to be cheaper at a commercial scale.

Recent research on ferrofluids, a liquid with small particles of iron mixed in, has brought that goal closer to reality.

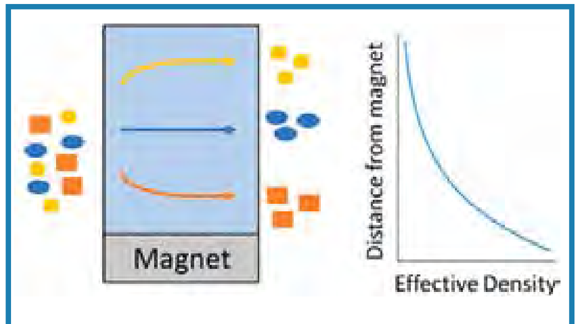
Scientists from the High Field Magnet Laboratory (HFML) and Utrecht University, both in the Netherlands, tested ways to optimize the iron-packed solutions so they could be used in large-scale magnetic density separation (MDS) facilities.

MDS is a technique used to sort items by their density. It has been used in niche applications such as diamond separation for some time, and a few recyclers have started to use it in small-scale pilot projects for plastics.

In MDS, a mix of plastics is chopped into small pieces then poured into a large container of ferrofluid positioned above a powerful magnet. Because the field strength of that magnet tapers off with distance, the particles in the ferrofluid spread out across a gradient, with more of them in the zone closest to the magnet. As a result, the effective density of any given layer in the fluid varies depending on its proximity to the magnet. The plastic bits float at the level that corresponds to their density, allowing recyclers to sort them into different grades.

Although this works fairly well at a small scale, ramping up production introduces a new set of problems, explains Hans Englekamp, an assistant professor at the HFML and a co-author on the publication resulting from the research project.

Image credit: Alex van Silfhout



In magnetic density separation, a magnet magnetizes a magnetic fluid and produces a field gradient, resulting in an effective density gradient used to separate plastics of different densities.

"The problem with large scale here would be that you need a magnetic field gradient across a large distance," Englekamp says. "That means you need big magnets."

But a stronger field causes the 10-nanometer wide particles in ferrofluid to clump together, ruining the gradient.

"One of the dangers is that they start to attract each other," explains Engelkamp. "So the project here was really to stabilize those nanoparticles."

To discourage the clumping, the research team added a citric acid to the ferrofluid that boosted the negative charge of the particles. The stronger repulsion between the particles was enough to overcome the magnetic attraction causing them to clump.

This more stable ferrofluid could make MDS useful for treating heavier recyclables, like those in electronics.

"If the ferrofluids are more stable, it also means you can use a higher concentration, and that means that you can have a higher magnetization per volume," says Englekamp. "And that means that you could separate higher density materials."

Image credit: Alex van Silfhout

The researchers experimented with different ferrofluids to create a stable solution in which the iron oxide particles would remain suspended even near a powerful magnet. In this photo of two different ferrofluids separated by a powerful neodymium magnet, the solution on the right remained stable. In the solution on the left, however, the iron oxide particles clumped together where the magnetic field was strongest.

Englekamp won't be involved in those projects, however. Although the research team used relatively high fields to develop the better-performing ferrofluid, they also demonstrated that future R&D can happen at lower fields.

That's exactly as it should be, Englekamp says. "We should discover stuff at high fields — that's what we do. But then later we should not be needed anymore. We want to pave the way for further development that no longer needs these expensive, very high magnetic fields." **— K.C.**

Combatting COVID

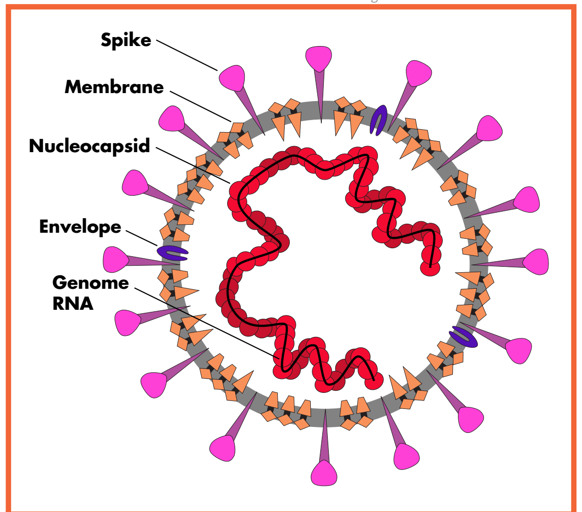
By now the mugshot of public health enemy #1 – the COVID-19 virus – is branded into our brains: a gray orb covered by an eerie forest of spikes.

But according to Elan Eisenmesser, an associate professor at the University of Colorado Medical School, potentially scarier are the proteins that lie beneath the sea urchin-like exterior of SARS-CoV-2. That's where the nucleocapsid protein wraps around the virus's genetic material, or RNA.

That structure, says Eisenmesser, may have a deadly dual purpose: to reach out and snag, like a wicked pirate's hook, the proteins of the body it has invaded and exploit them for its own purpose: infection.

For several months, Eisenmesser has been using powerful nuclear magnetic resonance (NMR) instruments at the National High Magnetic Field Laboratory in Tallahassee, Fla., to investigate this idea. He is comparing the behavior of these proteins to SARS-CoV-1, the virus responsible for the 2002-2003 outbreak. The two cousins resemble each other closely; in fact, their nucleocapsid proteins are 91% identical.

Image credit: Caroline McNiel



The SARS-CoV-2 virus.

Eisenmesser, who is in the Department of Biochemistry and Molecular Genetics, had studied the SARS-CoV-1 nucleocapsid more than a decade ago. So when the pandemic broke out earlier this year, he was quick to enlist in the fight against this related microscopic foe. His findings, he says, could elucidate possible treatments, research directions and drug targets.

There is strong reason to suspect that the nucleocapsid is doing more than just guarding the viral RNA in its tube-like armor, Eisenmesser says. It's not unusual for proteins to "moonlight" — or take on biological side gigs outside their primary functions. This seems especially likely for nucleocapsid proteins, which far outnumber spike proteins in the SARS virus family.

Another clue to a nefarious secondary purpose is the fact that some regions seem to be able to wiggle about within the structure. That motion may allow them to slither their way into a binding site on an unsuspecting host protein.

"If you think about it, it makes sense, because there's so much of this nucleocapsid surrounding all of the RNA," says Eisenmesser. "Some of the nucleocapsid could bind one host protein, some could bind another. It could also be cell-type specific, which is something that we're interested in looking at with our colleagues here, who include mass spectrometry experts." Part of the nucleocapsid might target eye cells, for example, while another might latch onto lung cells.

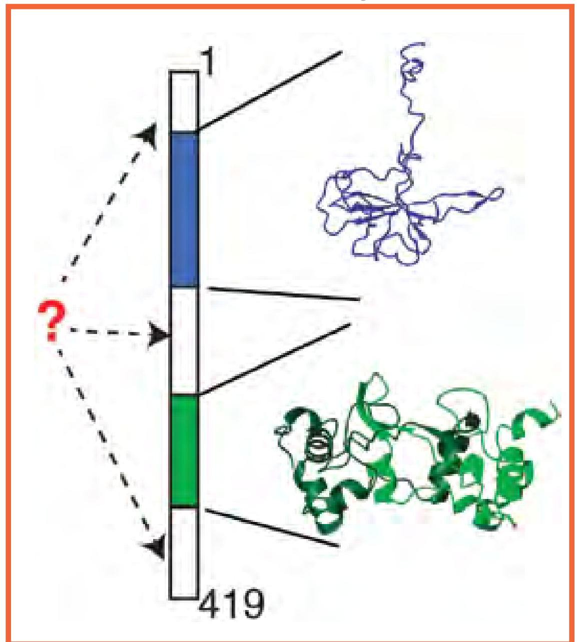
One purpose of this behavior, Eisenmesser suggests, could be to disable the immune cells, cytokines and other defenders that the body dispatches to fight the virus.

"It could tag and stop a protein involved in the normal innate immune response — basically just blocking it from acting as it would," he explains.

The MagLab's high-field instruments allow Eisenmesser to piece together, at the atomic level, the details of host-virus interactions. Like other scientists using the MagLab's facilities during the pandemic, Eisenmesser is conducting his experiments remotely; lab staff, in this case technical/research designer Ashley Blue, assist by running the instruments on site according to his instructions.

Specifically, NMR helps Eisenmesser identify the nucleocapsid regions that are dynamic, quantify the timescales of these dynamics and examine their interactions with various host proteins. He has observed that host proteins appear to target the more dynamic regions within the nucleocapsid. This is strong evidence, he says, that flexible portions of the nucleocapsid are dynamic in order to attach to the host protein.

Image credit: Elan Eisenmesser



Biophysicist Elan Eisenmesser has been studying the nucleocapsid from the virus that causes COVID-19. The structure is made up of 419 residues and includes two independently folded domains, one shown here in blue (a small N-terminal domain) and one in green (a dimerization domain), each corresponding to a different segment of residues. Little is known about the movements and the functions of the regions of the structure that are represented in white.

"They're not necessarily flopping around for no reason," he says.

"That's where NMR is so great," Eisenmesser adds, "because it can be used to screen proposed host interactions, using different parts of that nucleocapsid, and thereby identify which part is being used to target the host."

Methodically examining different scenarios may lead to discovering an interaction with a host protein already familiar to pharmaceutical companies.

"Something could be already in the pipeline or already clinically approved," Eisenmesser says. "So you could identify potential blocking reagents that exist already to block the nucleocapsid from targeting particular proteins." — K.C.

For more stories on COVID research in high fields, please visit NationalMagLab.org/covid

Ocean's Four: A Science Heist

A team of researchers pulls off a daring data caper in Delaware Bay, swiping secrets about the movement of molecules between air and water.

By Kristen Coyne

What is science if not an organized group effort to wrest bits of knowledge from the clutches of nature — in other words, a data heist?

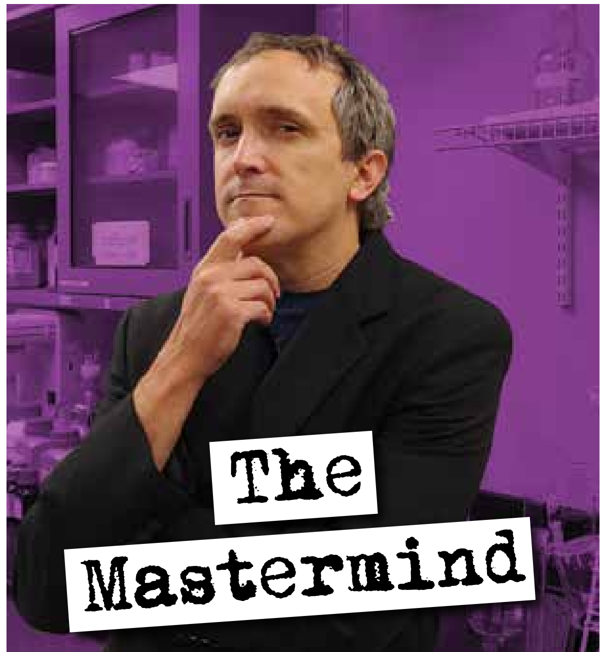
Granted: Science is a legal endeavor, while robbing banks or casinos can land you in the joint.

But think about it: A research project bears similarities to a well-planned heist. You need a mastermind (the principal investigator, or PI); muscle to do the work (grad students); one or two associates to lend their expertise (collaborators); and of course the all-important safe cracker to access the locked-away treasure (a data wrangler).

Like any good caper, a science project requires excellent planning, hard work, good timing and a little luck. But most of all, success depends on a talented, diverse and well-run team focused on one goal: Making off with the goods. For scientists, the loot comes in the form of insights into the inner workings of our world.

This is the story of one such squad, led by marine scientist Andrew Wozniak. Its mark: The ocean's surface microlayer, which mediates the transfer of molecules from air to water. The crime scenes: Delaware Bay, the University of Delaware and the National High Magnetic Field Laboratory.

In this anatomy of a data heist, we look at what each crew member pitches in to pull off this marine science sting. Let's call this quartet of investigators Ocean's Four.



Andrew Wozniak
Assistant professor, University of Delaware School of Marine Science & Policy

Teamwork Tip: "A team that plays like a team is better and bigger than the sum of its parts, and utilizes the strengths of each team member in a way that they end up with better quality work."

As project PI, Wozniak is the boss. He came up with the idea, informed by his expertise in carbon cycling, aerosols and how molecules pass between sea and air.

Image credit: Jonathan Cohen

One thing is certain: That path crosses the surface microlayer, the ocean's thin, skin-like veneer, which is both chemically distinct (more organic matter) and physically distinct (lower surface tension) than the water beneath.

"The layer between the ocean and the atmosphere controls the exchange of any materials that are coming into or out of the water," explained Wozniak. "That includes things like oxygen and carbon dioxide that can go in either direction but also things like dimethyl sulfide, an important gas for the climate that is produced by biological organisms."

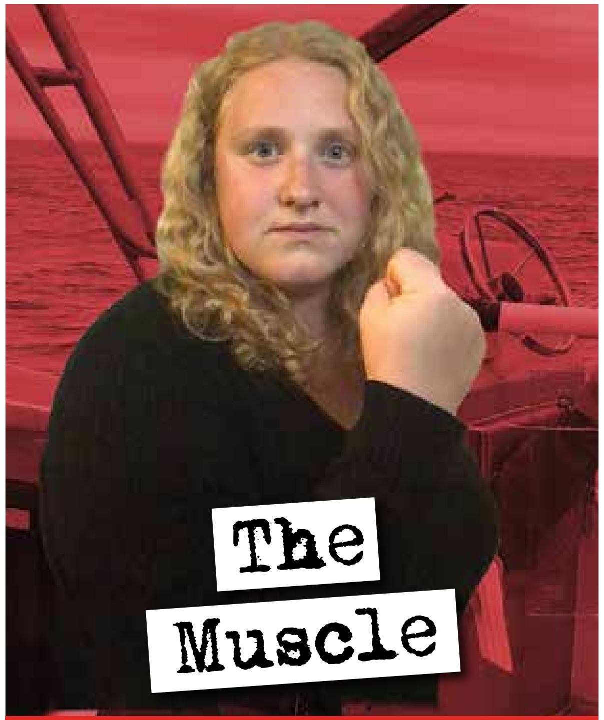
This microlayer plays a role in everything from air quality and climate to pollutant and carbon cycling. Yet much about its makeup and behavior remains a mystery.

"The basic questions that we're trying to understand," said Wozniak, "are: What controls the chemical composition of the surface microlayer? How do changes in the chemical properties change its physical properties? What does that mean for processes that exchange gases across the surface from the ocean to the atmosphere? And how does the change in the chemical composition affect really important processes that impact climate and carbon cycling?"

That's a lot of questions. To answer them, his team accumulated a lot of data, hoping to tease out the relationships between the chemistry, biology and surface tension of the microlayer and the underlying seawater. Their findings could help improve models of gas exchange, which plays a role in climate change and other processes.

But their ambitious plot needed money. As mastermind, it was up to Wozniak to find a way to bankroll his data heist. He reached out to the University of Delaware Research Foundation: They were in.

Wozniak also had to assemble his gang for the two-year project. On his list: an expert in marine microorganisms; an expert to crack the codes hidden in the haystacks of data they would generate; and, of course, someone who was eager, curious and driven enough to take on the brunt of the work.



Nicole Coffey

Graduate student, University of Delaware School of Marine Science & Policy

Teamwork Tip: "As a student trying to learn, there's so much you get out of being in a collaborative team. It helps you grow a lot more as a young scientist to have a team behind you as opposed to just one person. As brilliant as that one person might be, the multiple perspectives really help you grow."

Although Wozniak had the vision, connections and experience to get this heist off the ground, Nicole Coffey became the engine behind it. In fact, from day one the project was designed as a training ground for this science rookie, who completed her master's degree this summer before launching a Ph.D. in ocean and atmospheric sciences at Oregon State University. Her job was to do the lion's share of the work, from reading the literature to collecting samples on a sometimes cold, windy Delaware Bay, and from examining those samples in an ion cyclotron resonance (ICR) mass spectrometer at the National MagLab to piecing together what it all meant.

Nicole Coffey (right) and a fellow University of Delaware student collect water samples in the Delaware Bay.

In short, her job was to become a scientist, in a school-of-hard-knocks kind of way. In grad school, obstacles are part of the process by design.

The low point for Coffey came while processing her MagLab data, which identified thousands of different compounds in each of her samples that required sorting and interpretation. And she needed to repeat this process for each of her nearly 100 samples.

"Having it be the first time I'm really dealing with this kind of data, and having it be that huge of a data set, has been intimidating for sure," Coffey said.

After spending several weeks on the task, she plotted some of the data to make sure it looked right.

It didn't.

Alarmed, she showed her results to Wozniak. As her advisor, he has tried to resist the urge to helicopter mentor. "I have to take a step back and let them find the story in the data, rather than tell them what the story is," he said of his students.

He confirmed that something was amiss and suggested Coffey confer with chemist Amy McKenna, their inside woman at the National MagLab. An expert at operating the lab's ICR instruments and interpreting the data they crank out, McKenna quickly diagnosed the issue: Some of the compounds were misidentified.

It was an easy fix, but Coffey had to redo weeks of work just as COVID was bearing down. Although

there was some collateral damage (one laptop bit the dust) Coffey powered through, grateful for the judicious guidance from the rest of the team. As a young woman in science, she was particularly inspired by the support of her senior female colleagues.

"I think it's just good to see other strong women in science," Coffey said. "It's like, 'Yeah, I can do this!'"

One of those women was Jen Biddle.

Jen Biddle

Associate professor, University of Delaware, School of Marine Science & Policy

Teamwork Tip: "It's very common for me to collaborate with chemists and geologists. It's one of the things that keeps me interested in science, and it's a way to make sure I stay out of my comfort zone."

Numerous factors, such as location and season, affect what's in the surface microlayer. Another factor: the critters that live there. To identify the bacteria and phytoplankton that Coffey scooped up in her samples, Wozniak recruited colleague Jen Biddle to his crew.

It was an easy collaboration for Coffey: She knew Biddle from the university's chapter for Women in Marine Science, which Biddle advises. A microbial ecologist, Biddle is an expert on the microscopic but important creatures floating atop the ocean, some of which are unique to the surface microlayer. A frequent collaborator with chemists and geologists, she was gung-ho to initiate the gang into the finer points of her trade.

"One of my goals in my career is to make sure that we do environmental microbiology the right way," Biddle said.

Biddle showed Coffey the right way to collect samples: freeze her catch immediately, filter out the organisms, extract the DNA, send it off for sequencing. Then she helped Coffey untangle the data that came back. That was the hard part, requiring Coffey to learn computational biology, algorithms and custom software.

"One of the big concerns when you deal with this kind of data is that you have to know how to process it properly," Biddle said. "So I'm glad that we can provide the expertise."

Coffey's astute, interdisciplinary mind made her a welcome accomplice, Biddle said.

"What we've had happen before is that a student comes to my lab and says, 'I want to do this,' and then we wind up doing all of the analysis and making them their figure and they stick it in the paper," she said. "This has been sort of an ideal team to work with because all I have to do is offer suggestions and opinions and then Nicole just runs with it."

But marine life was just one piece in Wozniak's master plan. His squad also needed to know what else was floating in the surface microlayer. To achieve that goal would require the best tool in the world for that kind of analysis and an expert who, with the mental agility of a cat burglar, could infiltrate mind-boggling gobs of data and delicately pluck out the jewels.

Amy McKenna

Research Faculty, Ion Cyclotron Resonance (ICR) Facility, National High Magnetic Field Laboratory

Teamwork tip: "The perfect team is that one that has done their homework."

Amy McKenna has collaborated with hundreds of outside researchers over the years. In fact, that's pretty much her job. She's the bridge between the mastermind's brain and a jumble of data that, to the uninitiated, is as impenetrable as a bank vault.

The National MagLab houses dozens of powerful magnet systems that scientists from around the world use to study all kinds of samples. McKenna often works with the lab's 21-tesla ICR magnet, the strongest of its kind in the world. It generates exceptionally detailed, precise data on the chemical composition of complex substances.

Some researchers send their samples — everything from crude oil to biochar and from groundwater to proteins — to the lab for in-house scientists to test. But some, like Wozniak and Coffey, make the trip to Tallahassee in person for the unique chance to operate the world-record instrument under the guidance of experts. McKenna led them through their experiments, introducing Coffey to the nuances of high-field ICR.

"From an education standpoint it's important that you understand where the data is coming from," said McKenna. "I can explain a lot of things to them that are happening during the data acquisition, and they can actually see and learn on the fly."

Still, their two days of data collection was the easy part. Interpreting it, as Coffey came to find out, was another ball of wax. The ICR instrument can detect every molecule in a sample by its unique weight. So when your sample has thousands, or even tens of thousands, of different compounds, finding the parts that matter can be like spotting one particular Benjamin in a suitcase of unmarked bills. But with years of experience, McKenna can glance at a mass spectrum and pick out the relevant compounds.

"That is the major challenge, and that is something the MagLab has in place," Wozniak said. "They've been doing this for a long time. They've got their protocols and their systems, and they can streamline all that for you."

McKenna is just as confident in Wozniak's mastermind competence. He and his team had their data ducks in a row before coming to the MagLab: microbial composition, salinity, pH, dissolved organic carbon and surface tension. It's only after thoroughly analyzing samples using other techniques, McKenna explained, that you can successfully interpret the vast amount of data you get from ICR. Otherwise, it's like trying to open a lock with the numerals in the wrong sequence.

"If you start with the ICR, you're working backwards," she said. "What made Andrew's team so great was they already understood everything they possibly could about this system before diving in and looking at it molecule by molecule."

Wozniak's team may not have marched out of the place with $160 million, but their well-planned, carefully executed data caper would have made Danny Ocean proud.

Image credit: S-F

Navigating Ørsted's Copenhagen

BY KRISTEN COYNE

Copenhagen is a very cool city. Home of great design, bike culture and *hygge* (kind of a Danish approach to living well that roughly translates to coziness), it's well worth the visit. As the former home of science legends Tycho Brahe, Hans Christian Ørsted and Niels Bohr, it's an especially attractive destination for geeks. In fact, 2020 is the perfect time for the science tourist to explore Copenhagen because it's the bicentennial of one of the greatest feats in science history, Ørsted's discovery of electromagnetism.

Well, it would be the perfect time, were it not for the fact that we are all under the thumb of a global pandemic that has squashed the vacation plans of countless would-be travelers.

Happily, *fields* magazine is here to fill that void. True: Most of us have no way to physically transport ourselves to the Danish capital, thanks to COVID-19. But on these pages we can comfortably armchair travel to this unique destination. You can also go to **fieldsmagazine.org/copenhagen** to take the same trip virtually with a special Google Earth tour we created to celebrate this 200th anniversary.

Either way, this trip is worth the cerebral detour. Ørsted's discovery not only led to a technological revolution, it eventually paved the way for the powerful electromagnets, housed at special magnet labs across the world, that enable new discoveries about materials, energy and life itself.

This voyage allows you to follow Ørsted's footsteps through 19th century Copenhagen, where he worked as a pharmacist, discovered electromagnetism and aluminum, founded a technical college and lived with his large family for most of his long life.

Bon voyage! Or should we say, *Hav en god tur!*

1

University of Copenhagen

In 1793, at age 17, Ørsted moved from his native Rudkøbing to study at the University of Copenhagen. One of the oldest universities in northern Europe, it was founded in 1479. Ørsted studied pharmacy, the profession of his father, graduating in 1797 with distinction with a degree in the subject. In 1799, he earned a doctorate with a thesis on natural philosophy there. In the years that followed, Ørsted worked and continued to study the natural sciences, both in Copenhagen and abroad. He started teaching chemistry at the University of Copenhagen in 1800. In 1806 he was given a professorship in physics, a post he kept until his death.

2

Lion Pharmacy

Løve Apotek (Lion Pharmacy), the city's first pharmacy, was located at Amagertorv 33 from 1620 to 1971. Around 1800, Ørsted managed the place. The current building, which dates to 1908, is located on the Strøget, a pedestrian shopping area popular with tourists. It currently houses a store for the Swedish fashion brand Weekday.

3

The Royal Danish Academy of Sciences and Letters

Hans Christian Andersens Blvd. 35 is the address of The Royal Danish Academy of Sciences and Letters; this building dates to 1899. Ørsted served as secretary of the Academy from 1815 to 1851. The institution served as an important community to share his ideas, experimental apparatuses and discoveries. In 1816, he demonstrated to Academy colleagues the "galvanic trough apparatus" he had developed and that led to his 1820 discovery of electromagnetism.

4

Discovery of Electromagnetism

At this address (Norregade 21) one evening in April 1820, Ørsted observed electromagnetism while demonstrating an experiment to some students. Ørsted had developed a special apparatus — essentially an electrical circuit connected to a battery. He demonstrated that whenever he connected or disconnected the battery, the needle of a small compass near the circuit suddenly moved.

He knew, of course, that when you move a compass, the needle realigns with the Earth's magnetic field. But the compass had been sitting still when the needle deflected. Ørsted had finally demonstrated what he had suspected for two decades: that electricity and magnetism were somehow linked.

After some more experiments, on July 21, he published (in Latin) a paper on his findings, entitled, "The Effect of the Electrical Conflict on the Magnetic Needle." Some of his peers were skeptical at first. But as others confirmed Ørsted's results the discovery of electromagnetism was celebrated and went on to change the world. 1820 was also the year that Ørsted discovered piperine, a component of pepper. Afterward, he referred to that time as the happiest year of his life.

See for Yourself

Watch a recreation of Orsted's discovery of electromagnetism at Bit.ly/SeeThruSciOersted

5

Discovery of Aluminum

Ørsted lived and worked at this address, Studiestræde 6, from 1824 until his death in 1851. The University of Copenhagen built these new facilities in 1824. The courtyard complex included the chemistry lab, where Ørsted discovered the element aluminum in 1825. He found what he described as, "a metal lump, which in color and gloss somewhat resembles tin." He announced the finding in February 1825.

6

Polytechnic College

This building, inside the courtyard of Studiestræde 6, was the first home of the Polyteknisk Læreanstalt (College of Advanced Technology, or Polytechnic College). Ørsted founded the school in 1829 and served as its rector until his death. Ørsted modeled the school after the École Polytechnique in Paris, with a vision not for a practical "trade" school but for a school that was interdisciplinary and emphasized theory. The school was sited here until 1890, when it moved to Sølvgade 83, where another famous Danish physicist, Niels Bohr, was a student and, later, professor. The institution has since relocated north of Copenhagen and is now called the Technical University of Denmark.

7

Ørsted's Park

This park is named after Hans Christian Ørsted and his younger brother, politician and lawyer Anders Sandøe Ørsted. This bronze statue is of Ørsted the scientist. Another statue of his brother, who served as Denmark's prime minister in the 1850s, is also in the park. In his statue, the elder Ørsted's statue, you can see that he is conducting his famous electromagnetism experiment.

8

Assistens Cemetery

Ørsted died March 9, 1851, of pneumonia at the age of 73. He was buried in Copenhagen's sprawling Assistens Cemetery. He shares his final resting place with other famous Danes, including physicist Niels Bohr, philosopher Søren Kierkegaard and author Hans Christian Anderson. Anderson was a friend and referred to Ørsted as "Store Hans Christian" ("Great Hans Christian").

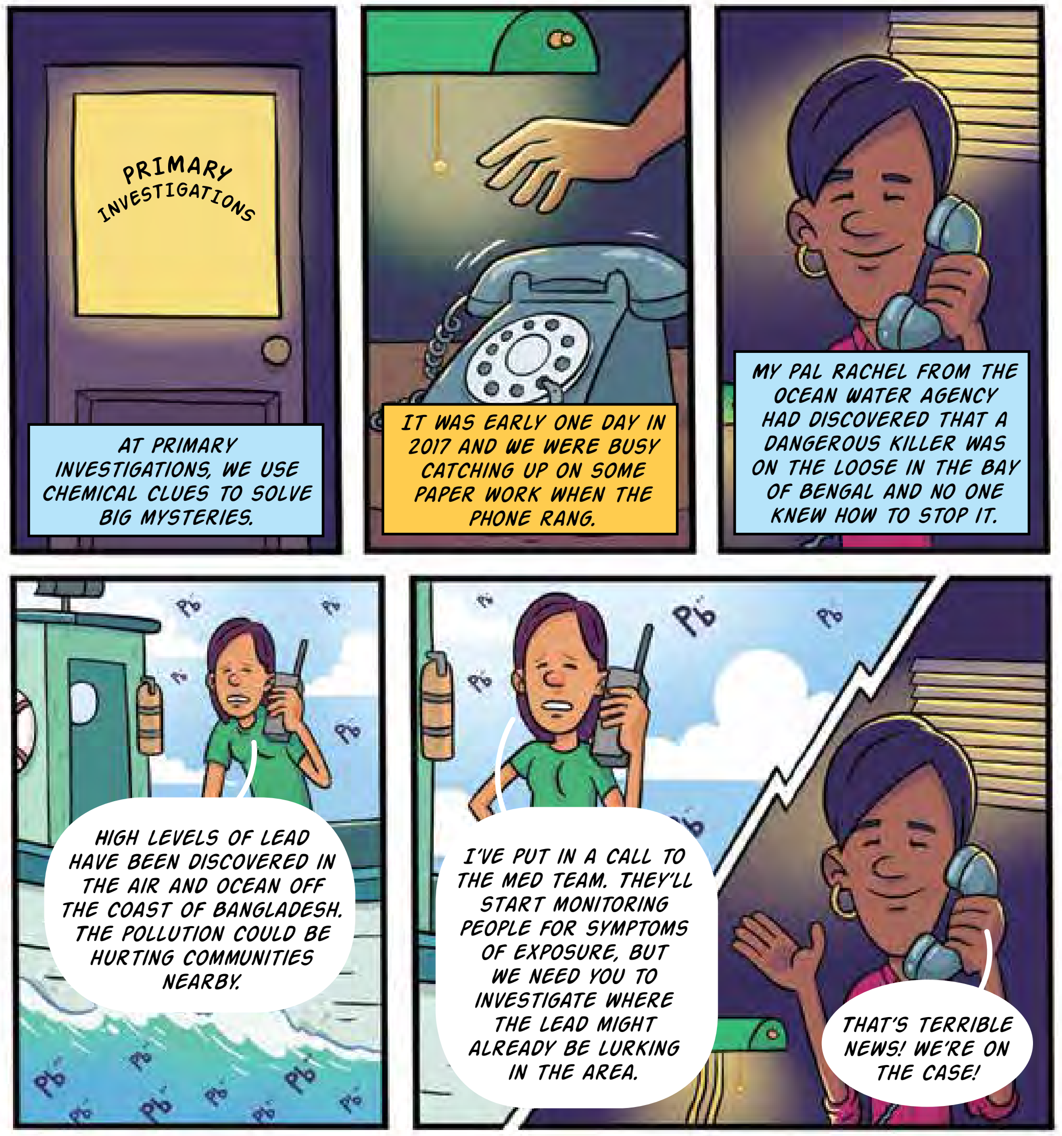
Lead and spice, anything but nice

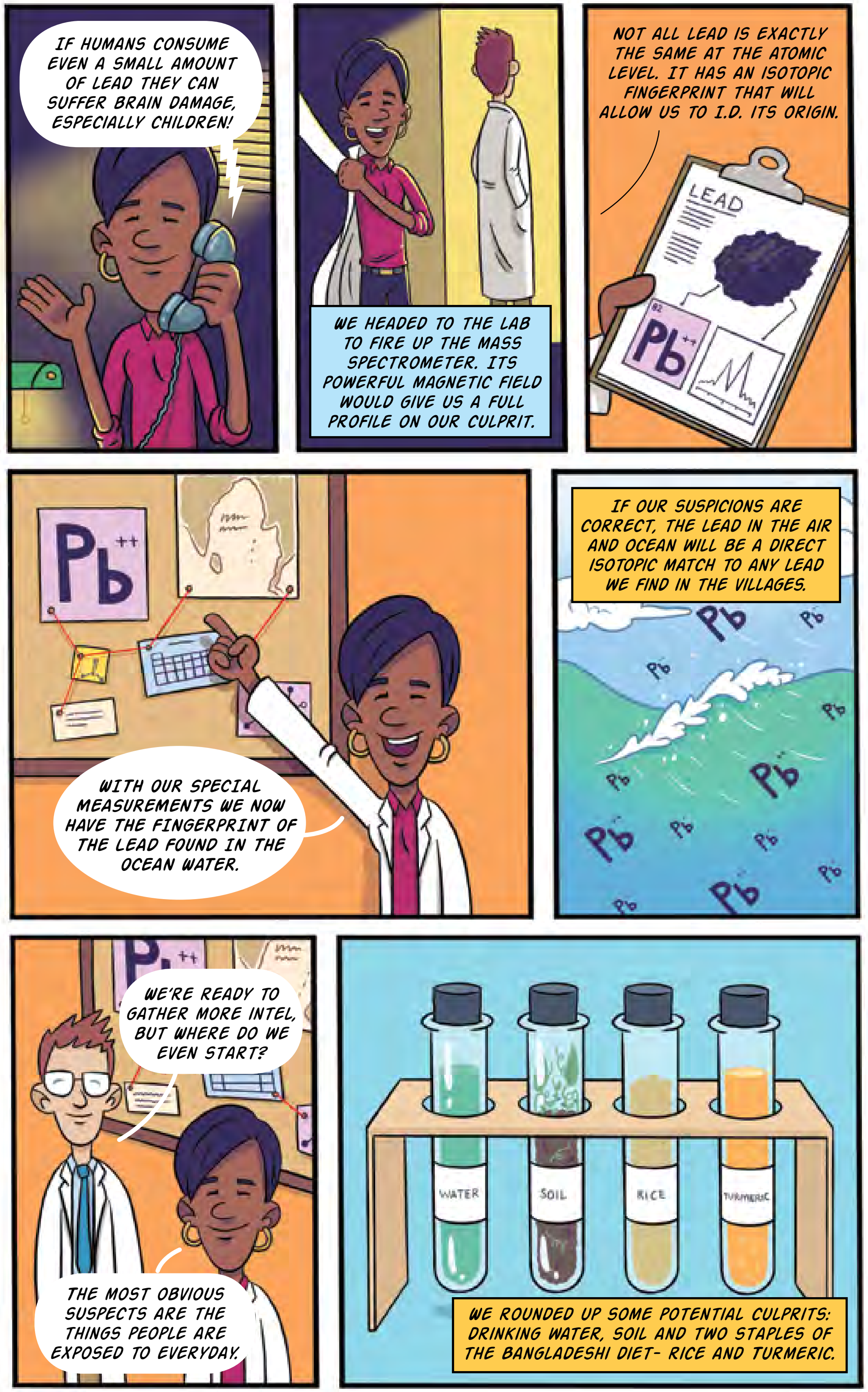
WRITTEN BY
CAROLINE MCNIEL
ILLUSTRATED BY
MARC THOMAS

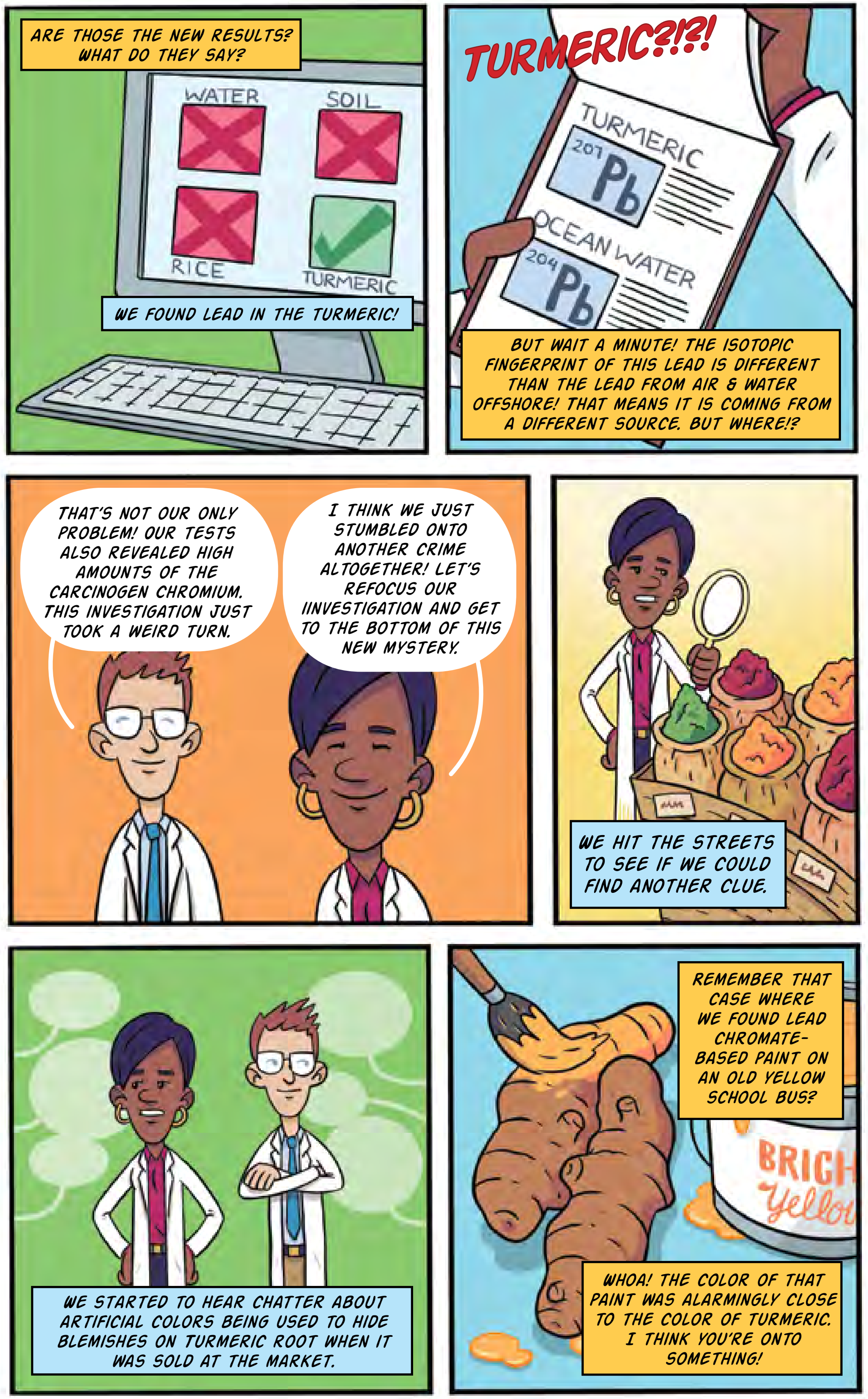
The discovery of lead in the Bay of Bengal launches a tortuous journey involving lead isotopes, turmeric and science heroes.

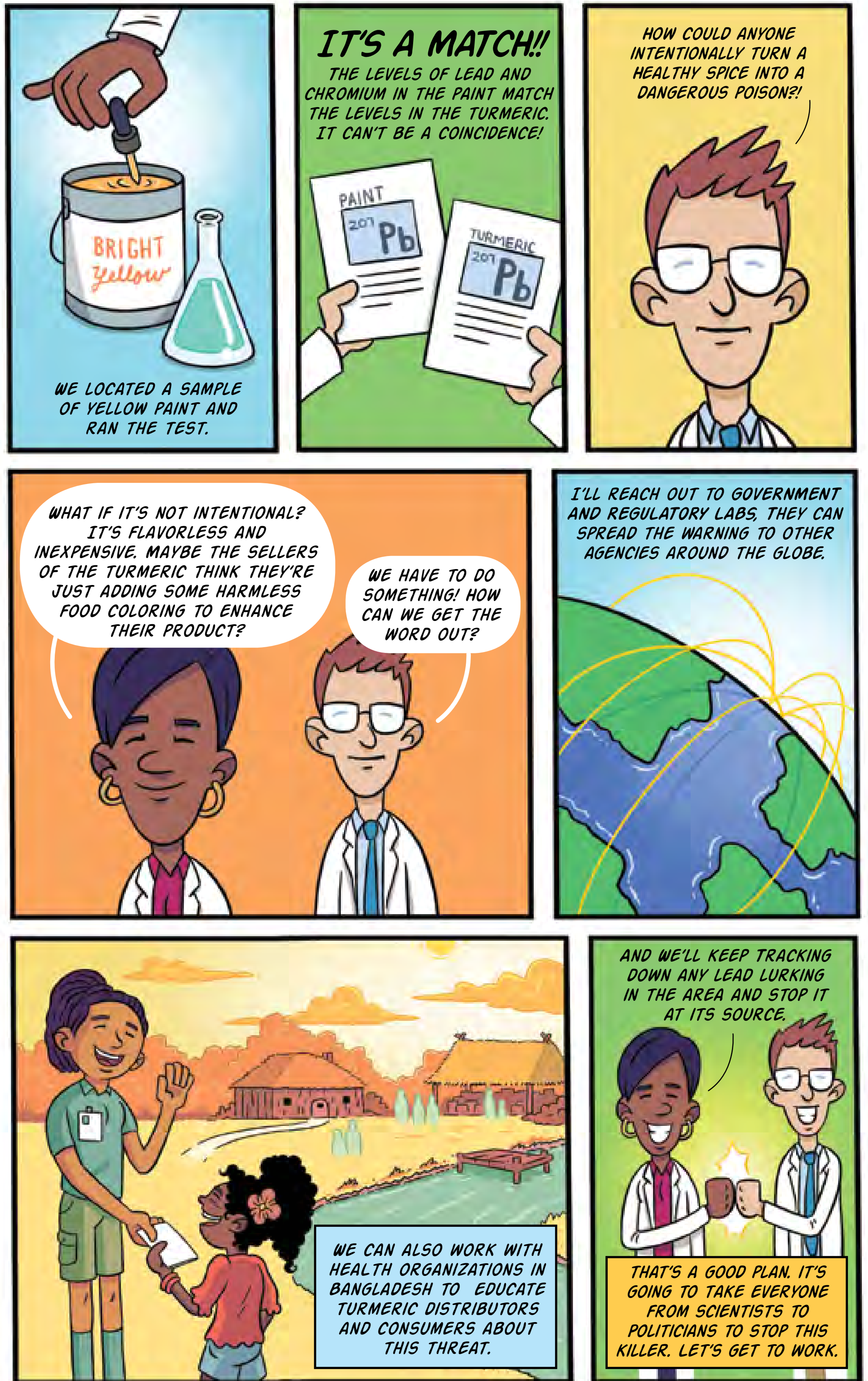
As a chemical oceanographer, Peter Morton never expected his research to lead him to the grocery store. But a project that started by testing ocean water samples ended up taking a strange turn — right to the spice aisle. Turmeric, a staple in the diet of many cultures, has garnered extra attention recently due to studies touting its anti-inflammatory benefits. As more people add the spice to their diets, Morton encourages consumers to be cautious: "Buy your turmeric and other spices from trusted vendors. The research project is ongoing, and the full scope of the issue is yet to be determined."

The work started as part of CLIVAR, an international project that investigates the complex movement of ocean currents, the chemical composition of seawater and the role of the ocean in the global carbon cycle. Morton, who works at Florida State University and the National MagLab, and his collaborators began by analyzing air and seawater samples from the Indian Ocean and discovered alarmingly high levels of lead circulating around the Bay of Bengal. That clue set Morton off on a hunt to track the dangerous heavy metal across the region. His adventure as the P.I. (primary investigator) on this research inspired the P.I. (private investigator) in the science mystery below.



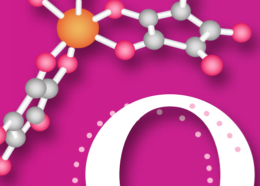


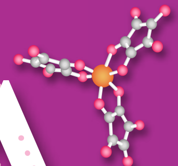




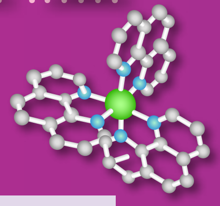
The researchers depicted in this comic represent hundreds of dedicated scientists and doctors around the world working to keep our spices safe. Find links to their research at fieldsmagazine.com/turmeric

Follow Morton on Twitter @SeaPeteRun for updates on this research and his adventures in geochemistry.





Qubit Q&A



Chemist Danna Freedman explains superposition, decoherence and how they all add up to the most fun you could have with science.

Illustrations by: Caroline McNiel

Are you curious about qubits, those cutely named building blocks of tomorrow's quantum information technologies? Well, join the qubit queue: Who *isn't* interested in the powerful machines that, in the decades to come, will revolutionize communication, sensors, measuring, cryptography — and who knows what else?

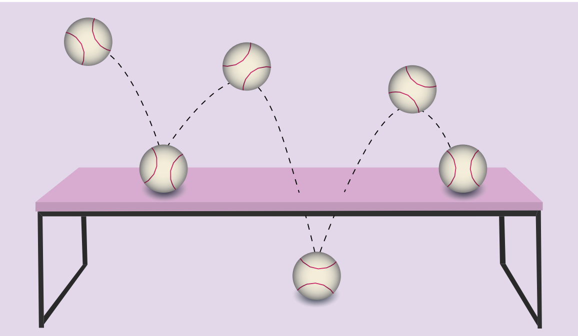
For most lay folk, qubits (or quantum bits) are a lot harder to understand than the conventional 1's and 0's we use to store or transport everything from tweets to spreadsheets. But those binary bits are destined to become digital dinosaurs, as scientists work to develop qubits that will displace them.

How do they work and when can you expect to find qubit-powered technology on your desk? Northwestern University chemistry professor Danna Freedman agreed to field our qubit queries. Freedman's group uses high magnetic fields and other tools to assemble and study molecules that could one day function as qubits. Read on and take your qubit cues from Freedman. — K.C.

Q We're about to get quantum! What advice can you give readers to prepare them to go from today's familiar classical realm to this quantum realm where everything is super weird?

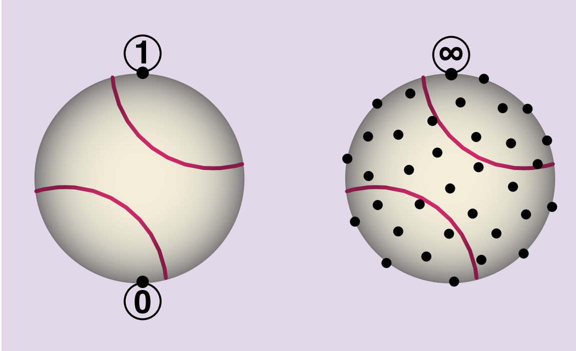
A Quantum completely defies our intuition. The fundamental idea is, when you enter quantum, you enter a space where nothing is absolute. Everything exists in a sort of probability distribution. So instead of saying, "We know the answer at every second," we say, "We know that it is *this* likely, under *these* conditions." This is something that makes sense when you're talking about a population, but a lot less sense when you're talking about a single particle.

If we think about a baseball bouncing on a table, it will always bounce up and down on the table. In the quantum space, if it was an electron rather than a baseball, you could picture it bouncing up and down, the way that your intuition expects. But every once in a while, it would just fall through the table. And that's completely crazy. It doesn't make



sense that at some probabilistic point, the electron will dive through the table. This is a really fun and crazy space that we get to exist in, this quantum universe.

Q Today's computers are based on basic units of information called bits, streams of electrical and optical pulses that represent information as either as a 1 or a 0. The term "bit" comes from "binary digit." But qubits aren't binary at all. Can you explain this?



A Instead of thinking about 1 and 0 as numbers, let's instead map them onto a sphere. Let's go back to our baseball, and we'll put a 1 on top and a 0 on the bottom. Now we have these two states that we've defined in a discrete way, and we can say we're going from one to the other.

Now let's move from a classical to a quantum space, where you say that this individual unit, this quantum unit, exists in all possible spaces. Instead of being limited to just two spots on the ball, your two values could be located anywhere on the sphere's surface. Instead of two states, you have the infinite number of states that form the surface of the sphere, and this is effectively how you can think about a qubit.

If you prefer to think about quantum mechanics more from a wave perspective, you can imagine two waves combining, and every combination of those waves existing at once.

Q How does that property of superposition — of existing in multiple places at the same time —make qubits so powerful?

A If you have 1,000 quantum bits in your quantum computer, each of which can be either a zero or a one, your quantum computer can represent all 2^{1000} states *simultaneously* [which is an unprintably large number! -*Ed.*]. The computer does not need to proceed through each possibility sequentially. If each bit has *multiple* values (say "m" values), then the quantum computer can try out m^{1000} states simultaneously, and this number goes up insanely rapidly as m goes from 2 to 3 to 4, etc.

Q What kind of problems is that useful for?

A To be glib about it, any problem for which a quantum algorithm has been written.

One important class of problems is the needle-in-a-haystack type problem, where you're searching over multiple configurations for one that works. We see this in everything from planning where sports teams will play each other to protein folding and configuration to doing high throughput analysis of drug protein interactions.

Then there's the class of problems that exists *because* of an algorithm. Back in 1994, mathematician Peter Shor invented a quantum algorithm for factoring large numbers (Shor's algorithm). This is really important, because the way that we encrypt data is based on the fact that we can't factor large numbers quickly. Shor's algorithm could fundamentally break encryption. This is one of the most well-established applications of quantum computing.

Q Could you talk about the challenges of superposition?

A With a classical computer, you define a bit that's 0 or 1, and you don't worry about it decaying: You don't worry that it will leave its 0 or 1 state.

For a quantum computer, we have a whole host of different challenges. The first one is that our bits are put into this fragile superposition state, which is a combination of 1 *and* 0 or up *and* down. The first thing that we have to do is make sure that the bits live long enough in this state. The collapse of the superposition state is known as decoherence, and is caused by interactions in the environment. So here we have the fundamental paradox and challenge of anything in a quantum universe: If you take a qubit, and you fully isolate it from the environment, it will live for a very long time — it will have a very long coherence time. But for any application of quantum information science, you need qubits to interact.

The next key challenge relates to the lifetime of these qubits, because when superposition collapses, errors occur. When you perform a quantum operation, it's inherently probabilistic: You might get the answer 99% of the time.

Currently one of the approaches to quantum computing is to develop quantum error correction, which helps you get the right answer *all* the time.

Q How do you make a qubit?

A A qubit is fundamentally anything that can exist in a superposition state: up and down, 1 and 0. There are a lot of different candidates for qubits.

One is a superconducting qubit. A lot of companies such as IBM and Google have invested in this technology, and it's compatible with current fabrication technologies.

Another large category of qubits is spin-based qubits. "Spin" refers to a property that some subatomic particles, including nuclei and electrons, have. In simple terms, you can imagine those particles spinning around an axis, like a top that can spin right side up or upside down. Scientists exploit that inherent two-state system in an up or down spin as a qubit.

There are electron spin candidates and nuclear spin candidates for qubits. In the nuclear spin category, the University of New South Wales is leading the charge in creating artificial atoms embedded in silicon. Another class of spin-based qubits is the defect-based materials. In these, the qubits are atoms residing within semiconductors or insulators. One example of such a material is the highly successfully anionic nitrogen-vacancy centers in diamond. These systems are generally fabricated by implanting ions in the diamond's crystal lattice.

Other important categories of qubits are cold atoms, where an atomic transition is used as a qubit, and topologically protected qubits, which are inherently protected from error. Also there are the so-called flying qubits, because physicists are really good at naming things. Those are just photons.

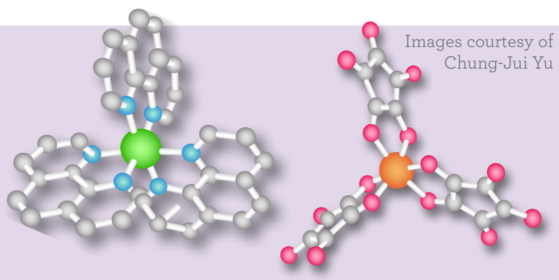
In my lab we work with spin-based qubits that are based in molecules. We're working on making systems similar to both the spin-based qubits in silicon and the defect-based qubits. But instead of top-down fabrication, we're doing bottom-up fabrication.

Q Could you describe that approach?

A We're using primarily electronic spins, but we're also looking at nuclear spin as a qubit. When you synthesize a molecule, you get to put every atom exactly where you want. Not only that, but you don't synthesize a molecule, you synthesize a lot of molecules, which offers potential for scalability. Every molecule in a sample is identical. When you take a tablet of aspirin, you take it for granted that every single molecule in that tablet of aspirin has exactly the same structure. And you also take it for granted that the bond distances between the atoms are precise down to a ridiculous level. In quantum applications, this high level of precision is absolutely essential.

Molecules allow you to have a high level of tunability for different applications. The design criteria for a quantum sensor and for a quantum computer do not match up perfectly, but with molecules, you can modulate the function by tweaking the molecule's structure.

We synthesize our systems using standard chemical synthetic protocols, very similar to how you would synthesize a drug candidate in the lab. Then we analyze them, for example at the MagLab, to acquire data about their coherence properties. We can execute hypothesis-driven science with molecules by asking, "If we move this atom, do we expect to increase the coherence time? Or will we decrease the photon contribution to coherence time?" So we can articulate a hypothesis, execute a test and get an answer, which is just really fantastic.



Images courtesy of Chung-Jui Yu

Freedman's group synthesized these two qubit candidates $[Ni(phen)_3](BF_4)$ and $(Ph_4P)_3[Fe(C_5O_5)_3]$ — and measured them at the National MagLab. Visit fieldsmagazine.org/qubits

Q So you build different types of molecules and then run them through these tests?

A Yes. And some of them had really good properties. For example, we demonstrated that molecules can have coherence times that are comparable to other spin-based qubits, about a millisecond. That was a really important concept and demonstrated that molecules are kind of in the game as qubit candidates.

We are currently working on different readout approaches — ways that you can read the data stored in a qubit — and making molecules compatible with established approaches. One way that you can see what the qubit says is using a magnetic field, by putting it in one of the instruments at the MagLab. In the defect-based candidates, you use light. There are different materials for building qubits, and then there's also the established technological infrastructure for determining what those materials are telling us. Creating new materials that integrate with a lot of these different readout approaches is very important.

If we can, from a molecular perspective, integrate with established readout technologies, then that really pushes the research forward.

Q What are the biggest obstacles to developing quantum information science technologies?

A On the quantum computing side, in my opinion, it's error correction. You get the right answer, but only some percent of the time.

More broadly in quantum information science, the biggest obstacle I would say is materials, tunable materials. The type of candidate that you would use for quantum metrology — exploiting quantum properties to execute precise measurements — would have fundamentally different properties than something that you want for one of these fantastical applications like a quantum internet. In both cases you're using materials where you can manipulate the quantum properties. But you need different forms of interaction and different properties for both.

Q So when will we see some of these technologies?

A I don't think there's going to be one day when all these technologies become a reality. In terms of quantum computing, we're in an era called the Noisy Intermediate-Scale Quantum or NISQ. There are certain classes of problems that we can look at with these early quantum computers, but it's not necessarily the type of problem that is of the largest interest to the general public.

I think it will take a couple of decades to access societally transformative problems.

As we scale up, we're going to hit interesting problems along the way. There are a lot of academic problems where you can begin to make a difference. Some of those are even in my own field of chemistry where, by coupling quantum computing modeling of problems with classical modeling, you can start to get more precise solutions to problems. You might even be able to push toward understanding fundamental processes of interest, like catalysis. Many companies that are invested heavily in quantum computing have their own published projections, and I would defer to some of these ideas. This is a highly interdisciplinary field, and my specific area of expertise is in constructing the core materials for quantum information science rather than implementing any quantum computation.

In quantum sensing, there have already been really interesting implementations. There's some really nice work on using qubits to map magnetic textures called skyrmions and on mapping protons in biomolecules. One of the aspirational goals of quantum sensing is to move to single molecule magnetic resonance, which is being able to map out the structure of one molecule in an ensemble. I think that's also a couple of decades away, but every step toward that will be a gigantic scientific achievement.

Q What got you into this line of research?

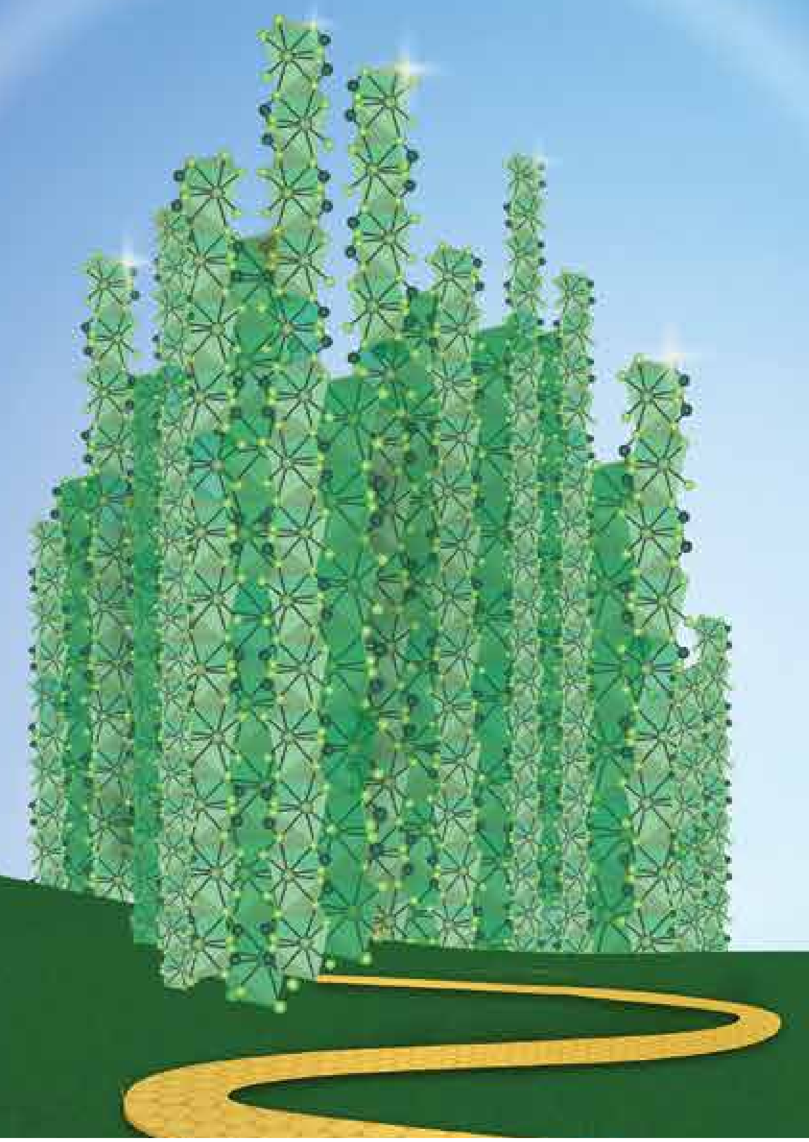
A Scientists don't know the answer! I love problems where we can create genuinely new science.

We can define so many questions and answer them and create new materials using the fundamental scientific principles of chemistry to explore an entirely new area. It's pretty much the most fun you can have with science.

Illustration by: Caroline McNiel

The Wonderful World of MOFs

By Bennett McIntosh



Follow us down this yellow brick road to learn how these deceptively small molecules conceal enormous potential for applications from carbon capture to data storage.

Imagine a set of Tinkertoys —

wooden nodes and colorful struts — so small that each piece is an individual molecule. Think of the endless variety of things you could build with it. Now imagine a kitchen sponge so porous that if you could somehow smooth out all the nooks and crannies it would cover 70 soccer fields. Think of how much it could sop up.

Although it may sound like a dream from over the rainbow, these two ideas actually describe the same thing: metal-organic frameworks (MOFs), a new kind of material with exciting applications from clean energy to data storage. But to make use of these materials, scientists first have to understand how they work, and that's where high magnetic fields are helping out.

First studied in the 1990s, MOFs have seen an explosion of interest in the last two decades. The Tinkertoy-like nodes are made of one or more metal atoms (the "metal" in MOF), while the long struts are made of carbon-containing molecules (the "organic"). The struts can be quite long for molecules, resulting in materials riddled with microscopic holes, channels and chambers. This makes them useful for absorbing gases for purposes from hydrogen fuel storage to carbon capture.

But it's not just their porosity that makes MOFs useful, says Monique van der Veen, an associate professor of chemical engineering at Delft University of Technology in the Netherlands. It's also their mind-boggling variety. Like many MOF researchers, van der Veen has also studied an older class of porous materials called zeolites. But because those are all based on the same combinations of aluminum and silicon, their uses are limited.

"However, with MOFs you have everything at your disposal," says van der Veen: Dozens of metallic elements can act as the metal nodes — copper, aluminum and zinc, oh my! — and an endless variety of organic molecules can serve as the linkers. This customizability, she says, makes the frameworks a playground for scientists like her.

MOFs can be customized to absorb a specific gas or tuned to respond to changes in temperature, pressure or their chemical surroundings. For example, a MOF could be designed to absorb carbon dioxide (CO_2) from power plant emissions or even from the ambient atmosphere. Another could be designed to absorb and slowly release 1-MCP (a gas that prevents ripening) to keep produce fresh without refrigeration.

It's a wild, wonderful world of MOFs (apologies to L. Frank Baum) — so wild, in fact, that we'll need a map to understanding it better. So we invite you to slip on your ruby slippers and follow along the yellow brick road as we explore this magical, microscopic Land of MOFs. Because, readers: We're not in Kansas anymore.

Along the way, we will encounter some fantastical figures: The Scientists of the East, North and West (using the National High Magnetic Field Laboratory, headquartered in Tallahassee, Fla., as our point of reference, where much of their science takes place). From their labs in the Netherlands, Ontario and California, these researchers (all working for good, not evil, of course) will be our guides, each using different ways to navigate inside MOFs.

Scientist of the North:
A high-field view of complex structures

Witches may fear the slightest drop of water, but many MOFs are born in it: The frameworks are usually synthesized in a liquid environment, which makes building MOFs quite a bit harder than linking together atoms and molecules like so many Tinkertoys. For MOFs to be any use, though, that solvent has to be removed.

"When you take the solvent molecules out, that can cause a dramatic change, like a change in MOF structure or even a total collapse of the framework," says Yining Huang, a professor of chemistry at Western University in Ontario and our Scientist of the North. "In some cases the changes are very subtle, but the subtle changes can have an impact on the MOFs' performance."

Huang studies how gases or liquids absorbed into a porous solid interact with it, so MOFs and their extremely high surface areas fascinate him.

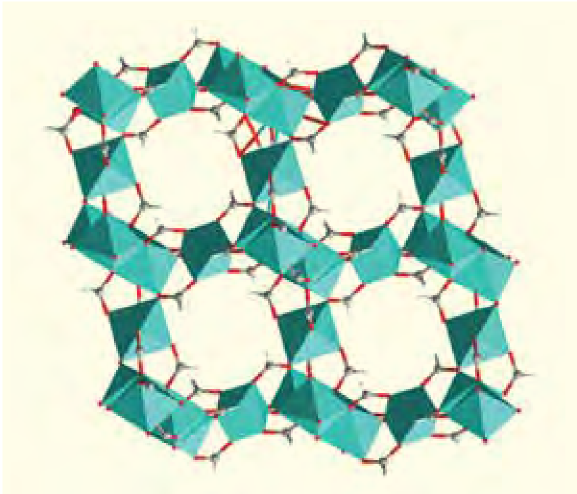
"The record is more than 7,000 square meters per gram," he says. "So in one gram of the stuff, you have more surface area than a soccer field."

One of the most important tools Huang uses to understand these structures is nuclear magnetic resonance (NMR) spectroscopy. NMR works by jostling around a particular element in a material — say, carbon — with a strong magnetic field. As the atoms wobble under the magnetic influence,


Yining Huang

Image credit: Vinicius Martins

Image credit: Jun Xu


Huang studies the MOF alpha magnesium formate, shown here in its "activated" state, ready for adsorption with empty pores.

they emit signals that tell scientists what other atoms — Zinc? Hydrogen? Other carbons? — are bound to that atom and how they're arranged. It's the next best thing to Glinda's crystal ball.

Researchers set up their NMR instruments slightly differently for each element, so someone like Huang can study each element in a MOF in turn.

"MOFs provide a dream for NMR people," says Huang. "You can look at the metal, you can look at the linker and you can look at what has been absorbed inside."

Each NMR experiment gives a panoramic view inside the MOF from a different atom's perspective, like a nanoscopic version of Google's Street View. But capturing those different views is challenging.

In 2017, Huang was grappling with one such challenge. He was using oxygen NMR to study a MOF by the ungainly name alpha magnesium formate, noted for its ability to selectively absorb CO_2. Once removed from a liquid bath, this material has oxygen atoms sitting at no fewer than 12 distinct positions. But oxygen is notoriously challenging to study with NMR, and instead of 12 sharp signals, Huang saw two blurry ones. That was enough to tell him the general structure of the framework but not enough to see subtle changes, like those that might occur when the solvent is removed.

That's when Huang met Zhehong Gan, a research faculty member at the National MagLab. Gan offered Huang the chance to try his experiments on a new NMR machine at the MagLab that produces a field of 36 teslas — the strongest magnet used for NMR in the world. Since the resolution of an oxygen NMR experiment increases with the square of the magnetic field, this would tremendously improve the resolution in Huang's previous studies, allowing him to get all the signals from oxygen atoms in their different positions in the MOF.

"The high field provides us with so many opportunities," says Huang. "Besides the oxygen in this work, we're also studying some of the metals in our other frameworks, like zinc and zirconium. These are tough nuclei to study, so we're fortunate to have this opportunity to solve these tough structural problems."

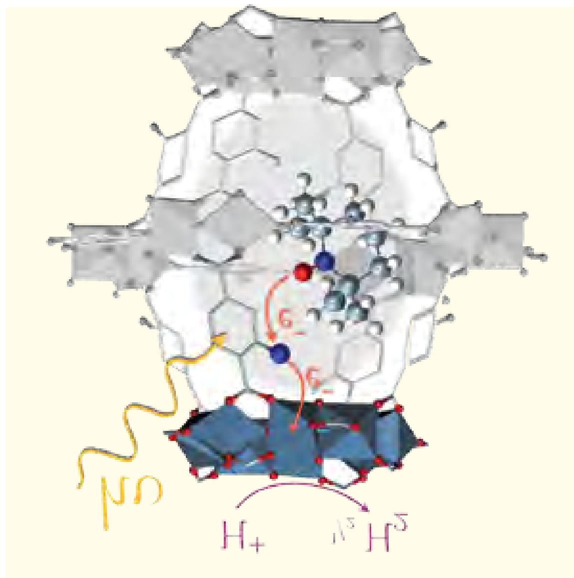
Scientist of the East:
Tracking electron traffic

If high-field NMR gives you the finest details of a MOF's structure, why would you ever need anything else? Well, imagine trying to find your way around a new place using street-level views alone. You can have as detailed a view of the yellow brick road as you like, but without an old-school map you'd have no hint of what strange features (A frozen tin man? A spooky forest?) pepper the landscape around it — and how those may affect your journey. Where you'd turn to a map to see how different places are stitched together, materials scientists turn to X-ray diffraction — the same tool that Rosalind Franklin used to take the first "pictures" of DNA's structure.

Franklin's diffraction differs only in details from the X-ray tools scientists like Huang or van der Veen use on MOFs. A beam of X-rays is scattered off a crystal, producing a pattern of lights and shadow that can be used to understand its size and shape. Are the atoms stacked directly on top of each other or interspersed like bricks? How far apart do the metal nodes tend to be?

But even with the most precise street map, you can still get caught in a traffic jam. So scientists need yet another tool, something akin to Google Maps' traffic layer. But instead of the flow of traffic, this tool reveals the flow of electrons.

Image credit: Jara Garcia-Santaclara


Monique van der Veen uses the interaction of light with a MOF to start chemical reactions of molecules inside the MOFs' pores. Here, a MOF called NH2-MIL-125 has adsorbed a molecule, the structure seen inside the gray MOF. Light (H_ν) is absorbed by the MOF, which induces the transfer of an electron from the molecule to the MOF.

For van der Veen, our Scientist of the East, how electrons move through MOFs matters as much as their structure. She uses optical spectroscopy to provide this traffic layer-like insight, measuring how her materials react to light in the visible spectrum.

If light makes electrons jump from the MOF to the absorbed gas inside, that could be useful in more efficient chemical manufacturing: Since molecules are held together by shared electrons, adding even one electron to the mix can be all the impetus a molecule needs to make a new chemical bond.

Van der Veen also uses optical microscopy to measure piezoelectricity in MOFs: If bending a


Monique van der Veen

framework makes electrons create a voltage, then it's piezoelectric and might be useful in generating green energy.

"I think in the next decade we will see MOFs moving into applications," says van der Veen. She predicts the first to be commercialized will likely simply absorb gas, but adds that, "I'm really interested to see how far we can get with conductive MOFs. They would open up a whole myriad set of new applications."

Scientist of the West:
Seeing through glassy MOFs

Mapping Manhattan's organized grid is a lot easier than making sense of London's tangle of streets. Similarly, many of these scientific mapping techniques only work on crystals: orderly, repeated lattices of atoms. Fortunately, most MOFs have a crystal structure.

But scientists like Sabyasachi Sen thrive in the disordered world of glass, which, like a swarm of flying monkeys, is disordered even at the smallest level, with each atom in a somewhat unique configuration. Because of this, glass is called an amorphous material, as are so-called glassy MOFs.

Sen, a professor of materials science and engineering at the University of California, Davis, and our Scientist of the West, has long worked with these wacky substances. He was originally trained in geochemistry, where he learned about the glass-like volcanic rocks that form when lava cools suddenly, and worked for many years at Corning, the glass company that invented Pyrex cookware and the Gorilla Glass that probably makes up your smart phone's screen.

Amorphous MOFs have the same building blocks as their crystalline counterparts but arranged in a disordered network. So the porous structure of

Image credit: Courtesy of UC Davis

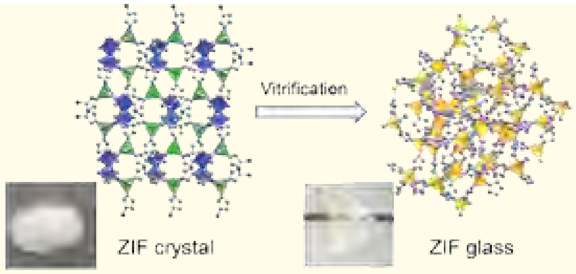
the MOFS can be preserved even when they are amorphous and could be used to store CO_2 for carbon sequestration, says Sen, or hydrogen gas for fuel cells. Also, because these compounds contain metals, they make for a glass that's far more stable than one made from carbon-based molecules alone.

Despite his many years working with glass, it was only recently, with the aid of MagLab researchers, that Sen was able to prove that the zinc-based MOFs he works with were truly amorphous — even at the smallest level involving the disposition of neighboring nitrogen atoms around zinc.

"Zinc is very challenging to look at through NMR," says the MagLab's Gan. But the world-record magnet at MagLab helped Sen and Gan pull back the curtain and see the true, glassy nature of these MOFs. The MagLab's research team also applied neat NMR tricks, such as spinning the MOF like an airborne home in a tornado at a so-called "magic angle" or using custom radio wave pulses to perturb it just so to coax information out. "We basically throw everything in," Gan says.

Now Sen knows he's truly working with glassy MOFs and is looking forward to more high-field collaboration with Gan.

"Even though we've never met in person, we have more than 20 papers together," says Sen. "They're brilliant spectroscopists who are coming up with new NMR techniques all the time, and they're



Sen studies amorphous MOFs, such as this zeolitic imidazolate framework. When turned into a glass, the structure retains the same building blocks, but now arranged in a disordered network. Yet the MOF remains porous, a property that could be exploited, among other things, for carbon sequestration in the future.

Image credit: R.S.K. Madsen, A. Qiao and Y. Yue from Aalborg University, Denmark; courtesy of Science.

always willing to mentor my students in terms of processing and interpreting the NMR data."

The Wizard of MOFs:
Mobile molecules for data storage

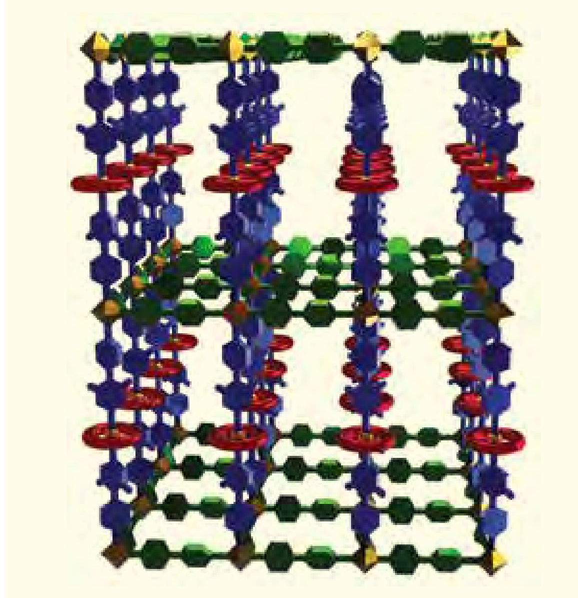
Our final stop across this Land of MOFs will be the Emerald City itself: The MagLab's Tallahassee headquarters (a capital city known, in fact, for its stately live oaks, pines and palms). Given this majestic address, we dub our next scientist, director of the MagLab's NMR Facility, the Wizard of MOFs. As befits the wizard of the Emerald City, chemist Rob Schurko's MOFs are crystalline. But in some ways they're weirder even than glassy MOFs.

With the aid of some very careful chemistry, Schurko and his colleagues in the research group of Stephen Loeb at the University of Windsor make MOFs in which the long linkers have other molecules wrapped around them, like a witch astride a broomstick. So the rings are mechanically, rather than chemically, bound to the MOFs' structure — lending them the name mechanically interlocking MOFs. Depending on what else has been absorbed into the MOF, these ring molecules can rotate freely, wobble about and even shuttle from one end of the stick to the other. But as long as the MOF framework holds together, they won't leave it.

This behavior could function as a Munchkin-size switch, says Schurko. The ring might move to one end of the linker in response to a specific stimulus — say a specific color of light — and to the other end in response to another.

"I think one of the grand goals would be something like data storage, where you have a 0 or 1 position literally down at the level of molecules," Schurko says.

Image credit: Benjamin Wilson, Stephen J. Loeb and Robert W. Schurko



Scientists are using MOFs like this one (called UWDM-3), featuring mechanically interlocked molecules, to design rudimentary switches, shuttles and machines at the nanoscale or molecular levels that could one day be used in applications like sensors, chemical separation, data storage or drug delivery.

There are other applications too. The rings provide a way to manipulate the shape of the pores so that the pores will preferentially absorb one gas over another. And if the rings can be convinced to move in reaction to the gas, and if that movement can be detected, then that MOF is suddenly a highly specific, low-energy gas sensor.

Schurko uses NMR to determine whether NMR spectra of the rings' atoms are sharp and clear — meaning the rings are held firmly in place — or "blobby," meaning the rings are free to wobble or rotate around the rod.

These experiments are much easier and more efficient when performed in high-field magnets, according to Schurko. "We have to do fewer experiments, and less fancy experiments, to get the signal we need," he says. "So, each experiment is more and more routine and reveals motions at the molecular scale that tell us a lot about how these materials work."

Close your eyes tight, click the heels of those ruby slippers together and repeat after me: When it comes to studying MOFs, there's no place like high fields.

Science S.O.S.

Illustration by: Caroline McNiel

Step No. 1 of the scientific process is: Ask a question. Sometimes, when things gets tough, that means asking for support. By Chris Patrick

Scientists encounter obstacles both in and out of the lab. Not every experiment goes as planned, and neither does life.

The three scientists in this story are no exception. Each has struggled with a different challenge, including finances, health, academic failure and career detours. But they all overcame them in the same way: They asked for help.

Science is, after all, a social endeavor. Scientists don't conduct experiments or publish research on their own, and they can't single-handedly clear every hurdle thrown their way, either.

Whether turning to a mentor, a friend or a professional, scientists say, the key is to find someone to listen, share wisdom and guide you.

Making ends meet vs. making good grades

Ashleigh Francis has juggled school and a job (sometimes two) since she was 16. She was raised by a single mom and money was always tight. The first in her family to go to college, she had to continue working while earning her undergraduate degree at Florida State University, even with scholarships and grants. Her 30-hour weeks at Bed Bath & Beyond made it difficult to keep up with schoolwork, especially because she usually worked the night shift.

Some nights, she wouldn't get off until 1 a.m., leaving little time to study or sleep. Although her grades were passing, tests usually brought them down.

"I was typically not proud of them," Francis, a physics major, said. "I felt like I was doing something wrong because I wasn't measuring up to my own standards."

She continued to feel inadequate until a friend and fellow first-generation college student shared her struggles. The conversation helped Francis understand that her problems with money, work and school were not her fault.

"I realized that there were actual challenges that I was facing that did make it more difficult, and I shouldn't be so hard on myself," she said. Identifying her obstacles, and talking about them with someone who could really relate, helped Francis believe in herself and stay in college.

So did research. In a physics class during her sophomore year, Francis saw a magnet levitate during a demonstration of superconductivity and thought, "That's the coolest thing I've ever seen."

Shortly after, she was hired as a lab assistant in the Applied Superconductivity Center (ASC) at the National High Magnetic Field Laboratory (MagLab).

"Even when I was struggling in classes, my job at the lab really motivated me to stay," she said.


Ashleigh Francis

Image credit: Stephen Bilenky

It wasn't just the science that made her stay; it was also the scientists. Her advisor, MagLab Chief Materials Scientist David Larbalestier, understood that she was a student first, permitting a more flexible schedule than her retail job so she could focus on school. Despite feeling intimidated, she developed positive relationships with mentors, including Larbalestier and Eric Hellstrom, a MagLab researcher and professor at the FAMU-FSU College of Engineering.

"My professors seemed more than human to me, so I was terrified to speak to them, thinking I'd look stupid," she said. "But they're people too."

Her advice for young scientists experiencing challenges as first-generation college students is to talk to people. Francis sees a therapist, leans on her boyfriend of 15 years and still turns to her mentors at ASC, where she continues working while earning her doctorate in materials science from FSU.

"I can go to them if I need to and tell them what's going on in my life," she said, "whether good or bad."

A diagnosis paves the way forward

After the first year of her doctorate at FSU, Alyssa Henderson began to realize something wasn't right.

"I just started shutting down," said Henderson, who spent long days at a desk programming for nuclear physics research. "I would hate going in."

While filling out a symptom questionnaire during an unrelated medical exam, she scribbled a question mark next to "depression."

"I wasn't sure if I had depression because I didn't feel sad," she said. "I felt nothing."

She was referred to a psychiatrist, who diagnosed her with depression and social anxiety. Henderson was conflicted about starting medication but began treatment after talking it over with her friends.

"I'm so glad I did because my life is so much better now," she said. "It's not hard for me to get out of bed in the morning anymore. I feel more like myself, I don't feel that null."

Henderson opened up to her roommates who, along with her beagle, Toby, helped

Image credit: Stephen Bilenky

Alyssa Henderson

her get through the tough times. “I lived with three of my close friends. I could tell them things and they were very understanding,” she said.

Just like Francis, she advises those experiencing similar issues to talk to people. “Whether friends or a professional,” she said. “Things can be a lot better. I think it is really important to not feel alone.”

Talking helped Henderson realize something important: She was in the wrong career. She ended up switching fields from nuclear physics to condensed matter physics. Instead of sitting at a computer, she began doing hands-on research, growing and characterizing quantum materials at the MagLab.

This worked out pretty well for Henderson. She recently finished her doctorate, published her first scientific paper as the first author and, after speaking in front of a packed auditorium, shared first place in a science-communication competition.

Sometimes a change of fields is just what’s needed to get over an early-career hump. Caleb McKinney calls this plan A′, using the scientific symbol for prime to describe a new career path.

McKinney helps students and postdocs reach their career goals as the assistant dean for graduate and postdoctoral training and development for Georgetown University’s Biomedical Graduate Education program.

“Most of my work has been helping young scientists set or reframe their career goals due to challenges,” he said. While he sometimes encourages students encountering obstacles to stick to their plan A, other times he helps them find a plan A′.

“I don’t like to think of it as a plan B,” McKinney said. “That sounds too backup-ish.” He found his own plan A′ in career development, after completing a doctorate and postdoc in microbiology.

“Be kind to yourself during turbulent times,” he said. “You have a lot to look forward to in your future, but remember that your current self is going to be doing the heavy lifting to get you there.”

Soaring after an academic nosedive

Today Jeremy Owens has a thriving career as a geochemist. He is an assistant professor of marine geochemistry at FSU, studies ancient climate change as a researcher at the National MagLab and was awarded a $75,000 fellowship from the Alan P. Sloan Foundation earlier this year.

Not bad for a guy who flirted with flunking out of college.

“As a scientist now, you win awards and you get articles written about you, but nobody saw you in those times of struggle,” Owens said.

Those times were in 2004, when Owens was a junior at the University of California, Riverside. During one quarter that year, he failed all but one class. He was kicked off the tennis team until he got his grades back up.

“It was one of those moments in your life when you look yourself in the mirror and you say, ‘Did I get really bad grades because I’m not smart enough, or did I get them because I didn’t really try?’” he said.

He decided it was because he didn’t try, which motivated him to manage his time more efficiently, put school first and study more. Translating his work ethic from athletics to academics helped him buckle down.

Before, Owens managed mediocre grades. But after his academic wipe-out, he made the Dean’s List every quarter.

“Without that moment, I probably would have just skated through,” he said. “It’s actually probably the best thing that happened.”

Image credit: Stephen Bilenky

Jeremy Owens

Owens’ path also involved a plan A′. He changed his focus from biology to environmental science and geology after his bad semester. Ancient climate change piqued his interest during a class with Timothy Lyons, a distinguished professor of biogeochemistry. But he had ruled out graduate school, assuming his GPA had sunk too low to get in.

Owens decided to share his concerns with Lyons. His professor not only helped him get into grad school but eventually became the advisor for his doctoral degree.

“Letting other people know about your struggle and not hiding from it can actually be useful,” said Owens. “Especially if you’ve learned from it and grown.”

In times of trouble, each of these three scientists learned that you can’t always go it alone.

“When students are sitting in front of me in a career coaching session, the first thing I say is, ‘I’m glad that you’re here and that you took the time to seek help,’” McKinney said.

After all, asking for help is really just another way of admitting you don’t have all the answers. And that’s a very scientific thing to do.

Asking for Help:

The How, the Where and the When

Caleb McKinney

If you are safety-conscious, you probably have a well-stocked first-aid kit stored in a closet or drawer. After all, mistaking the tip of your thumb for a garlic clove is not the best time to wonder if there are any bandages in the house.

Caleb McKinney urges us to think about mental health in the same way. “When you enter a space, make sure you know where all the resources are,” he said. “When you’re in crisis, it’s harder to navigate.”

McKinney, assistant dean for graduate and postdoctoral training and development for Georgetown University’s Biomedical Graduate Education program, said it can be hard for graduate students and postdocs to find those programs, which are often underfunded. But since 2018, when a high-profile article in Nature drew attention to mental health issues plaguing that population, things have been improving, he added.

Although large-scale solutions have lagged, grassroots efforts have emerged. Those programs can be hard to recognize — on purpose. “If you call it ‘wellness,’ people may shy away from it,” McKinney said. Instead, integrating wellness into everything from book clubs to job search training can build resiliency in these populations.

Although the COVID-19 pandemic has added another layer of stress and anxiety, one upside is renewed attention to the need for wellness resources, McKinney said. Another is that the growth in online counseling and group therapy has made help available to more people.

McKinney recommends checking out the website of the Office of Intermural Training and Education at the National Institutes of Health, which features a wellness section that includes a series on Becoming a Resilient Scientist. The National Postdoctoral Association also offers valuable resources and fosters community through discussion forums and a Tell Us Your Story program for postdocs facing bias, racism and social inequities.

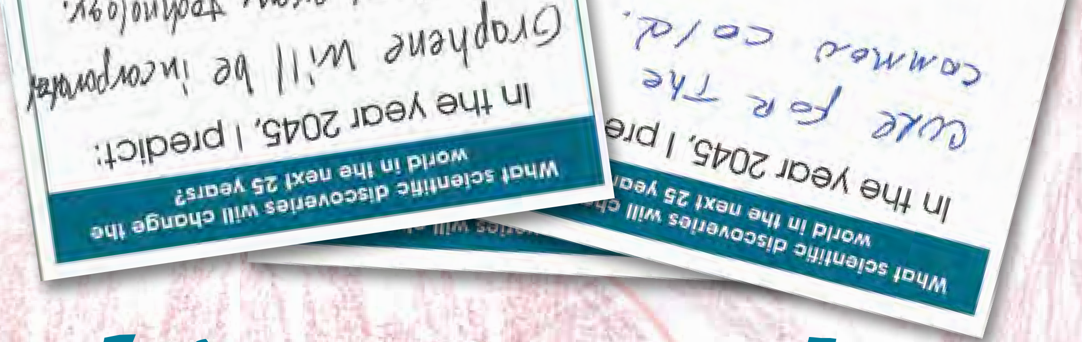
“Finding ways to stay connected is so important,” McKinney urged. “Stay connected with each other.” — K.C.

Image credit: Georgetown University Biomedical Graduate Education

Need Help Now?

211 In the U.S. or Canada, you can call this number to get expert, caring help. 211 is a source of locally curated social services information that connects millions of people to help every year. More info at **www.211.org**

Crisis Text Line This is free, 24/7 support for those in crisis available in several countries. In the U.S. or Canada, text 741741 to talk with a trained crisis counselor. In the U.K., text 85258 and in Ireland, text 50808. More info at **www.crisistextline.org**



ALIENS ATTACK!

Science predictions made by visitors to the National MagLab's 2020 Open House were funny, sweet, poignant and scary.

WHAT scientific discoveries will change the world in the next 25 years?

The nearly 10,000 visitors to the annual Open House of the National High Magnetic Field Laboratory were invited to speculate on that question, record their answers on slips of paper and add them to a time vault that will be opened in the year 2045. Ironically, just a few short weeks after these science prognostications were made, the coronavirus pandemic made big public events like Open House a thing of the past (for now, at least) in a way none of the visitors had predicted.

But before sealing the vault, we couldn't resist stealing a peak at some of the prognostications penned by those science fans, who ranged in age from preschooler to near-centenarian. And we're sharing that sneak peak with you.

They touched on a wide range of topics from travel to energy, from health to technology.

We will teleport, commute in flying cars and, predicted one baby boomer, "… finally get the jet packs they promised us as kids." Leaving fossil fuels behind, we will generate energy via the sun, nuclear fusion and, according to a 12-year old girl, "… at least begin to experiment with drawing power from the ionosphere."

The common cold will go the way of the plague, MRI scans will be much faster and asthma therapy will be tailored to the patient's genetic subtype. The "wonder material" graphene, a two-dimensional form of carbon, will be in all our gadgets and, even more thrilling, "there will be a way to locate lost keys instantly!" Robots of all types will abound. Our favorite: robot unicorns.

Some soothsayers interpreted "scientific discoveries" creatively: a future career as a vet, in the NFL or on Broadway. One 10-year-old girl predicted plaintively, "I will still be half the size of my brother."

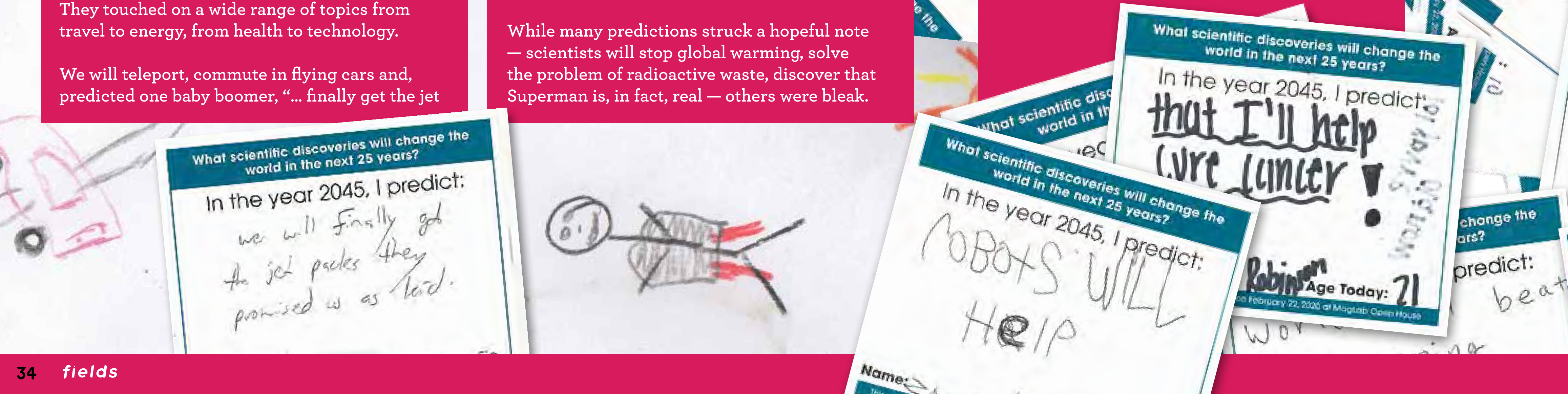
While many predictions struck a hopeful note — scientists will stop global warming, solve the problem of radioactive waste, discover that Superman is, in fact, real — others were bleak.

"Possibly the Earth will burn down and pollution will be everywhere and bombs and wars and bad stuff," summarized a 9-year-old. One young boy foresaw more of a mixed bag. On the downside, the world will melt and sea levels will rise by 25%; but on the upside, he will have a hologram watch.

Some predictions were poignant. People who had lost loved ones to cancer or other diseases imagined that scientists would finally find cures; one family, writing in Spanish, vowed they would still be united, "full of health, peace and love."

Others were laugh-out-loud funny. "Pigs will fly," one girl prophesied. Wrote one 13-year-old boy, "Cats will be more advanced than humans."

At least that seems funny now. But in 2045, when Fluffy programs the droid to kick you off her favorite chair, who'll laugh then? - K.C.



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These mild-mannered looking scientists are actually attempting a high-tech science heist. Find out what they're trying to steal on p. 7.

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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