Janet Conrad  Lead Professor and Originator of Course

Janet Conrad grew up in Wooster, Ohio. She became excited about particle physics while at Swarthmore College. After graduating in 1985, she attended Oxford University for her M.Sc. and Harvard for her Ph.D. She then spent 15 years with Columbia University, as a postdoc and then faculty. She moved to MIT in 2008, where she developed the 8.226 class. She studies neutrinos, a particle in the Standard Model with distinctly non-standard behavior. She likes to search for and follow up on experimental anomalies in neutrino physics, because she is sure nature is trying to tell us something new – if we just listen closely enough.

Krishna Rajagopal  Professor of Course

Krishna Rajagopal is a theoretical physicist who asks how the quarks that in ordinary matter are found confined within protons and neutrons behave in extraordinary conditions – like the trillions-of-degrees-hot quark soup that filled the universe microseconds after the Big Bang, which can provide a testbed for understanding how a complex world can emerge from simple underlying laws. Krishna grew up in Toronto, graduated from Queen’s University in 1988, and completed his PhD at Princeton in 1993. After stints at Harvard and Caltech, he joined the MIT faculty in 1997. He is currently the Chair of the MIT Faculty.

Michelle Tomasik  Physics Teaching Assistant

Michelle Tomasik is a Digital Learning Lab Fellow in the Physics Department at MIT where she works on creating and evaluating digital content for EdX physics classes and on-campus introductory physics. Michelle grew up on a farm in upstate New York, studied chemistry and physics at Swarthmore College, and earned her Ph.D. in physics at MIT studying interface effects on solar cell efficiency. She and Janet have now taught two classes together: introductory electricity and magnetism, and this class, 8.226. She has also taught introductory physics with Krishna.

Joshua Sokol  Writing Teaching Assistant

Joshua Sokol is a freelance science journalist in Boston. He provided guidance in writing for 8.226. His work has appeared in New Scientist, The Atlantic, The Wall Street Journal, and elsewhere. Like Janet and Michelle, he attended Swarthmore College, where he double majored in astronomy and English literature. After undergrad, he worked for a few years as a data analyst for the Hubble Space Telescope’s Advanced Camera for Surveys, and then pursued his master’s degree in science writing from the MIT. Currently, he covers astronomy and other disciplines of natural history.

Cover: Dark Matter Detective Lina Necib by David Sella. Inside: All photographs by David Sella.
Introduction

I think of the MIT Physics Department as being like one of the truly great, magical cities of the world—like New York City, where I lived for many years, or London, Paris, Jerusalem, Bombay, or Tokyo.

It is a vibrant, thriving and inspiring place to pursue science. Because of its size, it is organized into four separate Divisions, each its own borough. We have Experimental Nuclear & Particle Physics, Theoretical Physics, Astrophysics, and our own alphabet city: the Division of Atomic Physics, Biophysics and Condensed Matter. Each borough seems to have its own distinct scientific style, and yet when you look closely, you find they are united. Intellectual streets connect particle physics to astrophysics through the neighborhood of Dark Matter; astrophysics to atomic physics by way of the LIGO District; and atomic physics to theoretical physics through the (very hipster) Quantum Information Theory Quarter.

Because of its size and diversity, it is hard to sum up a great city in just one picture. Instead, one needs a series of snapshots. That is what this project is about. This booklet provides a snapshot of MIT Physics in the spring of 2016, through a series of articles on the research of graduate students across the department. Each story is written by a different undergraduate from the 8.226 writing course, which I taught with Krishna Rajagopal. This collection is in no way complete, and it isn’t meant to be. But it captures the range of creative scientific endeavors we pursue here and why it is a joy to be a part of the MIT Department of Physics.

Janet M. Conrad
Alex Tinguely

It’s official: our favorite spinning space-rock is in trouble. The Earth is rapidly becoming too hot to handle because we can’t stop consuming energy from fossil fuels. But, what if there were a way to unleash oodles of energy from extremely abundant fuel without producing harmful byproducts? A phenomenon so awesome that it lights the sun and every other star in the sky?
This process is called nuclear fusion, and the good news is, we can do it here on Earth.

The bad news, however, is that there are problems with our methods of harnessing it that make it impossible to use as a viable power source. Solving these problems could mean a bright future for our bleak energy landscape, which is what Alex Tinguely, a graduate student at the MIT Plasma Science and Fusion Center, is working on.

Tinguely is doing research on an impressive machine with an even more imposing name: the Alcator C-Mod Tokamak. It’s a device that, against all odds, allows us to achieve nuclear fusion reactions in the middle of Cambridge, MA. A fusion reaction involves taking two nuclei, the cores of atoms, and smashing them together so they become a single nucleus. This releases a lot of energy, because it takes less energy for hydrogen nuclei to exist bound together than it does for them to exist apart. That said, it isn’t easy to convince nuclei to get close enough to fuse, because they are positively charged and repel each other with colossal force.

It may be helpful to think of fusion like trying to get two people who hate each other to carpool: As difficult as it may be, once you manage to get them both in the same car, you save a lot of energy. Analogously, once you manage to get the hydrogen nuclei to fuse into a single nucleus, energy is saved by the combination. You can then use that extra energy to do useful things, like generate electricity.

Tinguely gets nuclei to smash into each other by getting them moving fast enough to plow through the barrier of electrical force. For hydrogen atoms in a gas, this means heating them to such a high temperature that the electrons are ripped from their nuclei, resulting in a plasma, a gas full of free charged particles. As exotic as they may sound, plasmas are common. Here on Earth, they’re responsible for the glow of fluorescent lights, the brightness of a flash of lightning, and the awe-inspiring shimmer of the polar aurorae. They’re even more mundane in outer space, where they make up much of the matter between stars, and the stars themselves. In fact, most natural fusion reactions occur in plasmas at the hearts of stars.

This gives us an idea of how hard it is to make fusion happen on Earth: we need to create conditions comparable to the inside of a star. Great for dramatic flair, but also great for melting expensive scientific equipment.

Unsurprisingly, hot star-stuff can’t be allowed to run amok on Earth: it would dissipate and never produce any useful reactions. “You have to somehow confine it,” explains Tinguely. “The Sun produces fusion energy, and it’s confined by gravity. If we wanted a reactor like that, we would need something the size of the Sun in order to have it confine itself, and we can’t have that on Earth, because Earth is like a million times smaller than the Sun, right? But what we can do is confine it with magnetic fields.”

That is exactly what the tokamak was designed to do.
A tokamak, such as the Alcator C-Mod, consists of a donut-shaped vacuum vessel that contains the plasma, which is prevented from touching the walls by powerful magnetic fields. The plasma interacts with the magnetic fields due to its abundance of charged particles. Jolts of current heat up the plasma to the necessary temperatures.

So, to recap, we have a clever setup of magnetically-confined plasma whizzing around at temperatures hot enough to produce fusion reactions. Why aren’t we using this to power the world? Unfortunately, there are problems that arise when you confine such an energetic material, and Tinguely’s goal is to solve them.

One of Tinguely’s research objectives is to predict events called plasma disruptions in the tokamak. A plasma disruption is, in Tinguely’s words, “the death of a plasma,” in which it rapidly loses energy and deposits itself on components of the machine. Disruptions often render the tokamak unable to continue generating power without undergoing expensive repairs. Tinguely is looking at measurements of parameters of the plasma, such as its position, velocity, and trajectory in the vacuum vessel as well as the current. “Just by looking at all the data we have, trying to create some sort of algorithm that, given another shot, would predict another disruption,” he says.

If Tinguely is successful in creating an algorithm to predict disruptions at Alcator C-Mod, it would be a ray of hope for the future implementation of tokamaks. When it comes to a plasma disruption, “if we can predict it, then we can try to prevent it or mitigate it,” he says. That would mean less damage to the equipment and a greater possibility of using it to generate usable power.

Another problem that arises in tokamaks is the issue of runaway electrons. Electrons are extremely light compared to the nuclei of atoms, so they move much faster in the plasma. If the electrons reach relativistic speeds, they can escape confinement and harm the device. The vessel and other components of the device can experience “in a sense, very small explosions just from being hit by a beam of really high energy electrons,” says Tinguely.

Using spectrometers inside the tokamak, Tinguely is measuring the radiation emitted by the accelerating runaway electrons in order to determine under what conditions they arise. If he can figure out the formation mechanisms, it might become possible to stop them from occurring or prevent them from damaging the device.

For both plasma disruptions and runaway electrons, figuring out how to prevent them or compensate for them is crucial for creating larger-scale fusion experiments, because it would be wasteful to spend so much time and money building a tokamak that’s going to destroy itself. Tinguely says, “if we can solve that, then we’re one step closer to having a fusion power plant producing net energy that you can put on the grid for the world to use.”

With regard to the awesome potential of fusion and the bright prospects of his current work, Alex Tinguely is optimistic. “I really think that it will be the energy of the future,” he says. “But hopefully, the near future, within our lifetimes.”

Amelia Smith is pursuing a Bachelor of Science degree in physics and linguistics. Her nebulous life plans include getting a puppy and maybe doing science or theater or something.
There are nearly $10^{30}$ bacterial cells on Earth – that is one trillion bacteria for every grain of sand on the planet! But despite their omnipresence inside us and around us, as well as their importance in soil and medicine, little is understood about how different types of bacteria engage in teamwork and warfare.
Arolyn Conwill, a physics graduate student in Jeff Gore’s laboratory at MIT, is working to fill this gap in our knowledge using new technology to quickly and accurately count bacteria. “The work is really exciting because there are a lot of new experiments that would not have been possible before,” says Conwill.

Bacteria are small cells containing DNA, much like their larger human cell counterparts. One bacterial cell can split into two identical copies in a process called division. This allows a large number of bacterial cells to accumulate if there are sufficient nutrients in the environment. A type of bacteria is successful if it divides quickly, outcompeting other bacteria. Interestingly, bacteria help humans process nutrients within our intestines. However, if those bacteria escape to another location in the body, they can cause an infection. Antibiotics are designed to stop the bacterial infection, by either killing the bacterial cells or disabling a key step in division.

At the same time, bacteria can develop the ability to grow in the presence of antibiotics, a phenomenon called resistance. When resistant and non-resistant bacteria live together, it can lead to what bacterial ecologists call the “cheater-cooperator” setup between two bacteria. The cooperator bacteria degrade the antibiotic around them and are thus resistant to it. The so-called cheater bacteria are not resistant to the antibiotic and will die in its presence – but if both the resistant cooperator and non-resistant cheater bacteria are grown together with the antibiotic, then even the non-resistant bacteria can survive. The cooperator bacteria degrade the antibiotic, reducing the concentration enough for the cheater bacteria to live. The idea here, as Conwill said, is “if the cooperators are deactivating some bad thing in the environment, then maybe the cheaters don’t have to.” This freeloading behavior from the cheater bacteria allows them to divide faster and more efficiently, because they forgo the work of degrading the antibiotics. Yet, without the cooperator bacteria, the cheaters would not be alive at all.

Previous experiments have studied the cheater-cooperator situation, but Conwill tested a setup in which this cooperation between the two types of bacteria goes both ways. Specifically, bacteria resistant to the antibiotic ampicillin survive in the presence of ampicillin but not chloramphenicol, another antibiotic. Chloramphenicol-resistant bacteria survive in the presence of chloramphenicol but not ampicillin. But when grown together with both ampicillin and chloramphenicol present, they both survive because they each degrade the antibiotic that would inhibit the other’s growth. Understanding this bacterial teamwork is the current focus of Conwill’s research.

Thus far, she has been interested in how many bacterial cells are present over time for each type
of bacteria while they work together. To this end, she performs laboratory experiments by growing both ampicillin-resistant and chloramphenicol-resistant bacteria in a fraction of a milliliter of liquid containing nutrients and both antibiotics. Over time, the bacteria divide many times and degrade their respective antibiotics. After twenty-four hours, she replenishes the nutrients and both antibiotics along with transferring one hundredth of the bacteria to a new container, so that the bacteria have more room to grow. She repeats these two steps of replenishing the antibiotics and transferring the bacteria each day for two weeks straight. To her surprise, Conwill found that the relative abundance of the two bacterial populations increases and decreases by four orders of magnitude every three days.

Her explanation for these oscillations goes like this: when there is a large amount of ampicillin-resistant bacteria in comparison to the amount of Chloramphenicol-resistant bacteria, then ampicillin will be rapidly degraded in comparison to chloramphenicol. Once most of the ampicillin has been degraded, the Chloramphenicol-resistant bacteria will be able to rapidly grow. This leads to a small amount of ampicillin-resistant bacteria relative to the large amount of Chloramphenicol-resistant bacteria. At this point the same logic applies with ampicillin and chloramphenicol reversed, resulting in a subsequent increase in ampicillin-resistant bacteria.

For Conwill, though, the bacterial teamwork experiment can be very time consuming, especially because she needs to vary an important parameter: the frequency at which she replenishes the antibiotics and transfers the bacteria. To speed up the work, she created a mathematical model and used a computer to simulate the experiment with different frequencies. These simulations allowed Conwill to understand the bacterial teamwork setup without performing thousands of laboratory experiments, which she says “would have been a total nightmare.”

In her simulations, Conwill found that the amount of each bacteria remains constant over time rather than oscillating if she replenishes the antibiotics and transfers the bacteria every hour. She tested the prediction by performing this experiment in the laboratory for twenty-four hours straight. Each replenishment and transfer step took her thirty minutes, leaving only thirty minute breaks in between. According to Conwill, half of the planning for the marathon experiment was finding enough “food that she was going to be able to eat really fast between time-points.” Fortunately, she maintained enough energy overnight and discovered that frequently replenishing the antibiotics so the concentration remains roughly constant does indeed stabilize the amount of each bacteria.

Besides day-to-day research combining experiments, models, and computer simulations, Conwill is a leader in outreach and her community. In April, she went to Washington D.C. with MIT’s Science Policy Initiative Group to discuss “science funding issues and encourage congress to continue and/or increase their support.” Conwill is also an avid baker: “a couple years ago, I decided that I would learn how to make really fancy cakes.” To improve her skill, she made each member of Jeff Gore’s lab a birthday cake. One highlight was a quad-copter cake for a high school student in the lab over the summer.

Conwill’s current results demonstrate and characterize bacterial teamwork in the laboratory setting. Going forward, Conwill hopes that her work will be expanded to include an evolutionary component. Perhaps after growing the ampicillin or Chloramphenicol-resistant bacteria together for a long time, researchers can observe some bacteria evolve resistance to both ampicillin and chloramphenicol, while other bacteria lose their resistance altogether. In conjunction with Conwill’s current results, she believes these experiments would help scientists better understand the mysterious details of antibiotic resistance in our food supply and bacterial infections.

Boryana Doyle is a rising senior at MIT, majoring in physics. After MIT, she hopes to attend medical school. Thus far, she has enjoyed advising freshman, sailing on Boston Harbor, and performing theoretical biophysics and experimental biology research.
We’ve learned a lot about atoms in the past 150 years. The atom has gone from merely a hypothesis to a staple of elementary physics, from the unknown to a symbol of science in pop culture. Atoms, we are taught, make up matter as we know it. But what are the components of atoms?
The nucleus of an atom consists of protons and neutrons, which in turn are made up of quarks.

In the same way that protons and electrons have electric charge in accordance with the electromagnetic force, quarks have “color” charge, which is carried by gluons, the particles that bind quarks together. The theory that describes this interaction is called quantum chromodynamics, or QCD. The primary goal of any theory is to successfully explain observable phenomena, but the observation aspect is difficult for QCD.

That’s because a fundamental point of QCD is the idea that you cannot separate two quarks. If you do, the energy in the gluon field will result in the spontaneous creation of another quark/anti-quark pair. We are able to study protons and neutrons by examining their interactions individually, but we cannot simply do this with quarks. As a result, creating experiments that test the validity of QCD requires a careful approach.

Thankfully, with the computation power developed in the last 50 years, physicists can simulate the behaviors of quarks and the particles they make up, through a process called Lattice QCD (LQCD). In LQCD, by choosing discrete points in space and time, and defining the strength of the interaction they want to model, scientists can solve numerically for solutions that specify the behavior and decay of quarks. Testing these solutions is the work of MIT graduate student John Hardin. Along with other members of the MIT Hadronic Physics group, he works on the physical hardware that will detect the products of predicted quark interactions.

But there is a catch – some of the mesons, a type of subatomic particle predicted by LQCD, have not been observed experimentally. The typical components of a meson are a single quark and a single antiquark, both of which contribute spin, charge, angular momentum, and other characteristics to the particle as a whole. There are strict rules about how those contributions relate to each other. However, some of the mesons predicted by LQCD have a momentum, spin, and charge that could not result from a quark-antiquark pair. The additional component would come from the excitation of gluons. These mesons, which have significant gluonic contributions, are known as exotic mesons.

If LQCD is a perfect representation of QCD, the nonexistence of these mesons would mean huge problems for the dominant theory in the field for the last 30 years – or imply that the methodology in performing the numerical calculation uses too many approximations to be useful. “A deviation from the spectra implies that something about LQCD is wrong,” says Hardin. If those mesons do appear, it would reaffirm the validity of QCD, and predictions based on LQCD would be limited only by computational power. So which is it?

In Virginia’s Thomas Jefferson National Accelerator Facility, known as JLAB, Hardin is trying to find out using an apparatus designed to solve this problem. JLAB is home to four halls – within each, specialized spectrometers are dedicated to investigating collisions with photons.
and a stationary target, usually protons. In Hall D, Hardin and his colleagues work on GlueX, which looks at the products of collisions between light and protons. These products often include mesons, which then decay further into other particles. By looking at the decay patterns, researchers can infer the characteristics of these mesons, and, most importantly, whether or not they consisted of one quark and one antiquark – or whether they are exotic. The ultimate goal of GlueX is to find all of the mesons predicted by LQCD, both exotic and already-observed.

In order for GlueX to achieve this goal, however, it needs an upgrade. The current way the detector identifies particles is a mixture of drift chambers, which provides particle tracks, a time-of-flight calculator, and calorimeters, which measure particle energy. However, at present the detector is not adequate to see all mesons predicted by LQCD. Two of the longest-lived mesons that will be detected by GlueX are kaons and pions. However, GlueX’s current particle identification system cannot distinguish between them, which means the distribution of meson products can’t be understood fully. In addition, seeing a kaon gives important information about the quark content of the meson – in particular, it is characteristic of a “strange” quark. “If you want to get the full meson spectra,” says Hardin, “you need to be able to identify strange content.” Upgrading the particle identification detector, or PID, to be statistically significant within a higher energy range will be extremely important for reproducing the mesons predicted by LQCD.

Building an upgraded PID has long been a priority. Hardin joined the group building the detector in 2012, when development was still in its infancy. The upgraded detector will use a special quark prism, called a DIRC bar. After hitting the target, the photons will travel through the DIRC, and emerge with an angle dependent on their velocity, producing a pattern like a fingerprint for the kaon or pion that made it.

The current PID is being calibrated, and the apparatus is being prepared for the installation of the upgraded PID, so Hardin commutes regularly between JLab and MIT. He spends 4-6 weeks per year on shifts, making sure data collection is running smoothly. As Hardin and his group prepare to build and install their upgraded PID apparatus, this amount of time will only increase. As of now, installation of the upgraded PID is scheduled for May 2017.

With improvements in simulations and the construction of the upgraded particle identifier on his hands, Hardin is quite busy. But the most interesting data collection won’t occur until the upgraded PID is brought to GlueX. Exotic mesons have long been hypothesized, but this will be a huge opportunity to observe them. No matter what GlueX finds, it will open the door to new questions. “If it exactly reproduces the spectra, that would be… interesting,” says Hardin. “Then we would get more computers, to do more LQCD.” But perhaps, a failure to precisely reproduce the mesons predicted would have just as much impact. It would raise questions as to how LQCD simulations were performed, and which assumptions they made, and raise questions about QCD itself. Either way, when data collection starts, we are sure to learn more about how the strong force works.

Elena De La Paz will graduate with a Bachelor of Science degree in physics with a minor in mechanical engineering in June. After graduating, she plans to work in San Francisco. For the past 4 years she has learned more than she could have ever imagined, and feels truly fortunate to have received excellent education as a scientist and engineer.
For all the glittering stars we see populating the sky, another unidentified material is thirty times as prevalent. Understanding this material, mysteriously named “dark matter,” is a unifying problem in physics that pulls together scientists trying to describe nature at drastically different scales—from galactic interactions to fundamental particles.
MIT graduate student Lina Necib works hard to solve this dilemma. With complex computer models, she sifts through mounds of astrophysical data, looking for the smallest suggestion about the identity of dark matter and how it interacts with known particles like photons and electrons. So far, dark matter has remained elusive, refusing to reveal its true nature, but offering hints along the way. “This problem in physics has grown over the past 20 years, especially in the past decade,” she says, and the payoff for solving it could be huge. “It might complete our picture of particle physics.”

But although the mystery of dark matter still haunts us today, it took a long time for physicists to appreciate the magnitude of the problem. Fritz Zwicky first stumbled onto the problem of “missing mass” in 1933 when he analyzed the movement of a group of galaxies. Zwicky found that more gravitating mass was needed than could be explained by the stars he saw. He wrote, “It is not certain how these startling results must ultimately be interpreted.” Yet, the disconnect between visible mass and unseen mass was dismissed for several decades.

The problem of missing mass was not understood until astronomer Vera Rubin came on the scene in the 70’s. She determined that there was a uniform halo of non-luminous material around galaxies, extending past their visible edge. Astonishingly, this mysterious halo composed the majority of the galaxy’s mass, pulling the stars into a complex choreography. “Think of it as a puppet show,” Necib says. Dark matter acts like hidden strings, rotating galaxies and pulling clusters together.

Finally, the hunt was on to discover what made up dark matter. “There were different theories,” Necib explains. “Either it is a particle that we don’t know, or it is modified gravity, which means we don’t understand the laws of gravity and that is why things are acting up.”

The best test in deciphering which of these theories held up came in 2006. Within the Bullet Cluster, two groups of galaxies collided and passed through each other. It was clear from X-ray observations that gas clouds from the two galaxies were colliding and heating up. Yet, using gravitational lensing to map all the gravitating matter, it became apparent that the majority of the groups’ mass passed through without colliding – something that normal gas could never do. Only an unknown particle could explain this: dark matter had to be a substance, not just modifications to our current understanding of gravity. But, the question remained: what is this particle? Even now, we still don’t understand it.

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Dark matter captivates Necib. From her early childhood in Tunisia, Necib was enthralled by
It was not just a path to understanding how the universe operated—it was a way to gain respect in a male-dominated society. Her drive to be a physicist has never waned. After completing her senior thesis on dark matter as an undergraduate at Boston University, Necib arrived at MIT ready to delve deeper into the subject. “When I came to MIT my advisor asked me, ‘Do you want to work on jets, dark matter, or supersymmetry?’” Necib says. “And I replied ‘Dark matter it is, because that seems awesome.’ So that’s what I’ve been doing over the past four years.”

To unravel its identity, Necib uses the standard model for dark matter—called the weakly interacting massive particle, or WIMP—as a foundation. The WIMP needs to explain a decade’s worth of odd data. Though Necib is a particle physicist, her data often comes from astrophysical observations. The vast scales, quantities, and exotic phenomena of the sky offer her a tremendous search area for dark matter.

While dark matter was first apparent as a missing mass, other anomalies across the sky may also be dark matter signals. As WIMPs can release gamma rays when two of them bump into each other and annihilate, any unexplained gamma ray emission could come from dark matter. Using gamma ray telescopes, Necib says, “There should be no place we don’t look.” Yet, observations of excess gamma rays alone are not enough to confirm the presence of dark matter.

Any detection of dark matter has to be verified in a second way. For instance, physicists are hoping to directly observe dark matter with detectors made of heavy nuclei like xenon or germanium that recoil or lose an electron when they interact with a WIMP. Physicists could also make dark matter by smashing protons together at the Large Hadron Collider. The goal is to observe WIMPs with the same characteristics in several experiments. With so many different ways to look for dark matter and so many different signals to parse, Necib says, “You have to be very open-minded in physics and basically let the data speak to you.”

Necib’s role is to calculate the rate at which dark matter signals may appear in experiments on Earth as the WIMP interacts with other particles. From these calculations, she can set bounds on the WIMP’s characteristics. Necib alternates between testing her theories with experimental data and using experimental results to make new theories. Remarkably, dark matter signals could already be lurking in the data, unknown to physicists. “Theorists have the job to actually suggest new experimental ways to find dark matter,” says Necib. “At this point you have to be more and more creative.”

MIT shapes how Necib searches for dark matter. “It’s a good place to explore your full potential. You are pushed to very, very high standards and very high limits. But still you have a lot of people around to help you,” she says. As a graduate student, Necib faces setbacks on a daily basis. Sometimes her code is buggy; other times her computer has issues. When she makes a plot to compare her most recent model with the data, she waits, staring at the screen. The plot finally pops up, and it looks wrong. But, a few iterations later, her understanding grows and the plot is beautiful.

Necib’s day-to-day struggle to understand the data parallels the larger problem physicists face in unraveling the nature of dark matter. The life of a dark matter detective is tedious and often frustrating. Each scrap of understanding takes an enormous amount of time and patience. But, this is just the type of task that Necib thrives on—technical and hard.

Ana Glidden graduated in June from MIT with a Bachelor of Science degree in physics. She plans on pursuing research in astrophysics after enjoying her experience with the Undergraduate Research Opportunities Program. In her free time, Ana enjoys backpacking and canoeing.
A silent explosion rocks the very fabric of space-time. The perpetrators of the chaos – two massive black holes – have ended a journey of epic scale. Caught in each other’s gravitational grasp some point long past, the singularities have spiraled towards each other for an unknowable time, circling like boxers before the first punch.
Together, the black holes weigh in at over sixty times the mass of the sun and the ultimate collision and combination turns three suns’ worth of that mass straight into energy. This energy becomes ripples in reality, gravitational waves, radiating outward as final, fleeting evidence of this cosmic clash.

These ripples made waves of a different sort 1.3 billion years later: they became the first gravitational waves detected by humans. The Laser Interferometer Gravitational Observatory, LIGO, caught the vibrations flitting through the Earth in late 2015. A true feat of experimentation, the discovery astounded and invigorated the worldwide physics community.

It was, however, simply the next chapter in a larger story for Nancy Aggarwal, a Ph.D. candidate in physics at the Massachusetts Institute of Technology. Hailing from India, Aggarwal graduated from the Indian Institute of Technology Bombay in 2011. At IIT, Aggarwal’s high school love for math and physics translated predictably well into university—"I was that kid who didn’t like anything else!"—and she immediately began pursuing a degree in physics. Although not much of a tinkerer prior to college, she nevertheless decided to explore experimental physics. “All of my classmates, everyone was doing theoretical physics,” says Aggarwal. “I think I took it as a challenge.”

But she observed a profound gender bias in her college cohort. “People know how to solder things, people have worked with Legos,” she says. “I wasn’t really doing that when I was a kid, and I saw it was the same for other women around me.” So Aggarwal began mentoring women in science and technology, saying, “Hey—you can do this. This is not something that has to be only men.” She decided experimental physics’s hands-on culture would allow her to further blaze the path. She remembers thinking “I want to change the face of this—I want to be that woman who’s interested in robotics and who’s interested in making things with her hands.”

Committed to experimental physics, Aggarwal moved to MIT’s Kavli Institute post graduation. Since then she has worked with Professor Nergis Mavalvala, studying and designing quantum-optical systems to further improve the sensitivity of the LIGO observatories.

When Aggarwal arrived, LIGO’s search had proceeded for eight years without seeing a gravitational wave. Scientists agreed that LIGO’s noise floor, the point at which internal fluctuations in the detector shroud useful signals, was too high. Important parts of this noise floor come from the quantum mechanics of the lasers LIGO uses to detect gravitational waves. Aggarwal’s work focuses on lowering these particular noise sources with quantum states of light called “squeezed states.”

Squeezed states are a consequence of the quantum mechanical uncertainty inherent in measuring light. Light has two principle measurable qualities: power, which is essentially brightness, and phase, which describes what point the light currently inhabits in its electromagnetic cycle. Light’s inherent uncertainty can be shared equally between power and phase, as is the case for laser light. In squeezed states, however, careful manipulation has “squeezed” uncertainty from one quality into the other. It is this exchange of uncertainty between power and phase that will prove invaluable for lowering LIGO’s noise floor.

One source of quantum noise in LIGO is shot noise—the uncertainty in measuring flows of distinct objects solely due to their distinct nature. The laser LIGO uses to detect gravitational waves
is a flow of distinct photons, and the resultant shot noise creates uncertainty in the laser's phase. Laser interferometers like LIGO work by measuring phase precisely, so this is a problem.

LIGO could decrease shot noise by increasing its laser power. The more powerful a laser is, the more photons it makes. With more photons, each individual photon is less important to the big picture, washing out shot noise and decreasing phase uncertainty. This solution, however, is not perfect. Increasing laser power comes hand in hand with increasing the power's uncertainty. Greater uncertainty in power leads to greater uncertainty in the bouncing force the laser's photons exert on mirrors in LIGO. This uncertainty in force leads to an uncertainty in the mirrors' movement, as if they are being buffeted by a gale of photons. This mirror movement ultimately raises the noise floor, making it harder to see gravitational waves.

It turns out that this phase versus power uncertainty tradeoff is fundamental to lasers. "There isn’t really any getting away with it," says Aggarwal, because it comes down to the same quantum uncertainty that causes squeezed states. But this means that squeezed states can offer a solution: if inserted correctly, squeezed states can exchange power uncertainty with phase uncertainty for the whole LIGO system. By controlling the type of squeezing, scientists can therefore control the uncertainty exchange, even tailoring it for listening at different gravitational wave frequencies.

Here, Aggarwal hopes to contribute conventional methods using advanced lenses to generate squeezed states. This only works at certain laser wavelengths, however, constraining the lasers LIGO can use. Further, conventional squeezers require meticulously aligned, room-sized optical setups to operate. Aggarwal wishes to create squeezed states without these lenses.

Aggarwal begins by creating resonance cavities out of two tiny mirrors, suspending one of the mirrors on a thin, spring-like piece of metal. When a laser shines into the resonance cavity, the suspended mirror recoils from photons hitting it, changing the length of the cavity and its corresponding resonance frequency. This effect is analogous to the way a guitar string vibrates at higher frequencies when you move your finger up the fretboard. Any uncertainty in laser power becomes uncertainty in cavity length, and therefore uncertainty in resonance frequency. This frequency uncertainty becomes phase uncertainty as the light leaves the resonance cavity. Overall, the system takes some of the laser’s power uncertainty and turns it into phase uncertainty – a squeezed state is born.

Aggarwal’s system is noteworthy for two reasons. First, the lensless design means it can create squeezed states at any laser wavelength LIGO could want. Second, Aggarwal’s squeezer design lends itself to a convenient, self-contained package. "We have squeezers, but currently they take a room full of space and three Ph.D. students to make," says Aggarwal. By contrast, Aggarwal’s squeezer is quite compact – no larger than a piece of carry-on luggage. "I could imagine," Aggarwal continues, “putting it in a box and just giving it to LIGO, saying ‘Hey LIGO, here’s this box, and that’s your squeezer.” These words hint at a deeper implication of Aggarwal’s work: ease of scaling. As LIGO, propelled by its success, begins to establish further observatories around the world, the convenience and flexibility of Aggarwal’s squeezer will allow for expedient implementation of squeezers in new systems.

Still, the work is ultimately very personal for Aggarwal. "I designed and built the entire experiment in an empty room," she says, “from designing shelves to designing very small and precision measurement components.” The system is her creation – not only designed with her mind, but also built with her hands. In an intellectual whirlwind of quantum physics and gravitational waves, Aggarwal still challenges that bias against hands-on, practical work she discerned in college. Now a mentor of a different sort, Aggarwal leads by example, squashing both scientific and societal barriers with each squeezed state.

William Rutter graduated with a Bachelor of Science in physics in June 2016. He is now pursuing a career in design and communication with the hope of spending life listening to and telling stories of all stripes.
Consider, for a moment, the millenia of collective endeavor, the dedication of countless careers to the understanding of the nature of interactions between two isolated particles. From the rigid body collisions of Sir Isaac Newton to the field interactions of Feynman and Schwinger, the struggle of fundamental physics has been to grasp at a deeper understanding of the simplest possible processes.
In light of this history, it is a daunting truth that the world around us consists of condensed matter: systems of unthinkably large numbers of particles acting in concert. How can we ever hope to understand this reality if our two-body models are still incomplete?

Spencer Tomarken, a graduate student at MIT, is working towards such an understanding by probing pure samples of carefully arranged matter with cutting edge experimental techniques. He dedicates great time and effort to preparing the perfect sample and performing the perfect experiment. His samples are idealizations of more common objects in terms of their purity, structure, and the conditions of their testing. Nevertheless, if Tomarken can reach through the complexity and isolate a new behavior, then he has learned something fundamental about the microscopic life of matter.

The key to studying these systems, says Tomarken, is emergence. Emergence is the appearance of collective, coordinated phenomena in many-particle systems. In Tomarken’s words: “If you can understand one particle, it feels like you can understand N particles, but, in fact, you can’t. You would never be led to something like superconductivity by understanding the nature of a handful of particles and then generalizing.” He says: “The whole point is that you get something which is greater than the sum of its parts.”

There is a gulf between fundamental and emergent phenomena that reductionist methods cannot bridge. Theorists must build models that can predict emergent phenomena using clever analogies and incisive approximations, rather than ground-up constructions from small-scale interactions. Perhaps the most important of these theoretical constructs is the quasiparticle. Although they appear in all kinds of physical systems, the quasiparticle of greatest interest to Tomarken is the “electron quasiparticle”. This entity can be visualized as a free electron which has been “dressed” by the electromagnetic fields of the matter through which it propagates. As it travels, the pull of these fields will alter the interactions and mechanics of the particle, causing it to appear heavier or lighter than the bare electron. These quasiparticles are the focus of Tomarken’s experimental work in graphene.

Graphene is a single sheet of carbon atoms linked together in a hexagonal “honeycomb lattice”. Elegant theoretical models exploit the symmetry and repetition of the lattice to produce simple models of non-interacting electrons. The reality of these systems, however, is a complex interplay of electrons as they skitter across the surface. Electron interactions in graphene are significantly augmented by the lattice “dressing” effects. Electrons under the influence of these abnormally large interactions, called “strongly correlated electrons”, are notoriously difficult to model. Tomarken summarizes the state of the theory as “contentious” and submits that it is up to the experimentalists to explore the subtleties of these interactions. “We’re the ones, on the ground level, answering questions,” he says. “I have this many electrons, ... how do they organize themselves, and how does energy minimize itself? Often it’s counter-intuitive.” They must find ways to listen for interactions among the overwhelming buzz of disorder. This is Tomarken’s art.

His research group, headed by professor Ray Ashoori, has developed a technique of unprecedented sensitivity for measuring the energy structure of thin condensed matter systems. Since matter is quantum mechanical in nature, its constituent particles may only occupy a discrete set of energy levels. The configuration of a quantum system will have a telling signature in the pattern with which its component particles fill these energy states. Due to the crystalline structure of materials like graphene, these energy levels separate into distinctive bands. Through great experimental effort, these bands can be mapped out in detail.

Tomarken is working on the application of a novel experimental method, known as tunneling
spectroscopy, to the exploration of graphene. He begins by fabricating single layers of pure graphene, and then sandwiches them between two layers of insulating material (one thick and one thin). The outside surfaces of these insulators contact conductors. Tomarken applies an electric potential across the contacts, which causes electrons to “tunnel” through the insulators and fill the graphene layer. It is a fundamental quality of nature that no two electrons can play exactly the same role (“occupy the same state”) in a physical system. As a result, when electrons fill the graphene, they will be forced to settle into progressively higher energy levels. The top filled level is called the Fermi level.

Once the electrons have piled up to the Fermi level in the graphene, Tomarken applies a rapid voltage pulse, saturating the conductor on one side of the graphene (the side with the thin insulator) with electrons. These electrons will tunnel through the thin insulator layer into the graphene, and then slowly trickle down (in energy) to the Fermi level. Crucially, the rate at which electrons with a given energy tunnel into the graphene depends on the number of empty states available at the energy in question. If the tunneling energy is near a band of states, the current will be large. If not, electrons will only trickle through. By varying the size of his voltage pulse and measuring the current at each step, Tomarken traces out the density of energy states, illuminating distortions in the band structure. These distortions are the signatures of electron-electron interactions within the graphene, and can be identified by comparison to the predictions of a non-interacting model. If Tomarken injects electrons slowly, and at energies far away from the Fermi level, the data will closely match such a model. The closer the incoming electrons are in energy to the Fermi level of the graphene, however, the stronger the interactions. By narrowing this energy gap, Tomarken isolates the physics of interacting electrons.

Asked what he hopes to find, Tomarken replies that there are familiar effects, like magnetic interactions between pairs of electrons, for which he is on the lookout. In the bigger picture, Tomarken says, he is really searching for surprising new physics. Graphene may exhibit unexpected emergent phenomena due to the strength of electron interaction. The challenges of theoretical prediction have left much of this territory uncharted, so the form of these phenomena, if they exist, is still a mystery.

Tomarken admits that the research can be frustrating at times, fraught as it is with false starts, faulty samples, and failed experiments. “To make one device, it could take two to three weeks, and the odds of that being a perfect fabrication are maybe one in ten,” he says. “So you could spend six to nine months making samples that just fail. There are so many things that have to coalesce and work perfectly to do this measurement.” Despite these frustrations, Tomarken says the thrill of leading this exploration keeps him going. “I touch everything and know everything about it. I’m the master of every detail. The upside of this is that you are in control… you nurse [the experiment] all the way through. It’s a very cool feeling to bring one of these projects to fruition. It’s your baby.”

Tomarken sees an exciting future for this work in graphene systems. Using techniques less sensitive than his, experimentalists are already exploring the dynamics of overlapping sheets, which produce complex quasiparticle behaviors. To add to the excitement, electron quasiparticles in graphene behave as if they are effectively massless. This strange behavior is responsible for the strength of electron correlation, and it may cause distortions in the response of these quasiparticles to external magnetic fields. Looking forward, Tomarken says, “We hope to explore physics that no one else has been able to access.” Armed with a powerful tool for probing complex systems like graphene, he says, “You trust that at high magnetic fields and low temperatures, you’re going to see something interesting.”

Zander Moss is a rising senior at MIT, majoring in physics and mathematics. He has had a great deal of time studying the physics of neutrinos with Professor Conrad and her research group, and he hopes to continue to explore nature wherever he ends up next.
In our universe, many mysterious and beautiful objects are invisible to the naked eye – but we have created ways to see them. Telescopes, science’s most traditional method, use portions of the electromagnetic spectrum to study celestial bodies.
For example, most amateur astronomers use visible light to see objects like stars or the moon.

Scientists are also developing techniques to use other types of waves to scan the sky – giving us a better look into the unknown.

Gravitational waves are ripples in the fabric of the universe caused by high-energy objects and interactions – like two black holes merging together! These waves stretch and squish the length of the objects through which they pass by an incredibly tiny amount – a fraction of the size of an atom. LIGO, the Laser Interferometer Gravitational-Wave Observatory, is the leading institution for detection and analysis of gravitational-wave signals. “In maybe 40 years, 50 years, we could see everything through gravitational waves,” notes Ryan Lynch, a current graduate student in the physics department at MIT. Lynch started working on the LIGO project as an undergraduate researcher, eager about the possibility of discovery. “We were turning on the upgraded instruments … There was a possibility that I was going to be one of the ones that detected things.”

Lynch is a working on statistical methods for fast signal detection and processing for the MIT LIGO project. Developing methods to accurately and quickly detect signals is a key step in gravitational-wave astronomy because it will allow us to “hear” the violent and beautiful outcries of the universe, making Lynch’s research very powerful for furthering insight and knowledge of the universe.

In Lynch’s line of work, he has to find ways to separate the important sounds of the universe from the background noise. Imagine you are given a list of characteristics describing the voices of 5 different people. Furthermore, you are standing on a busy street – many cars and beeping horns – and are asked to distinguish a person’s voice from the background noise. Given the noise of the cars, people etc., imagine how difficult it would be to accurately distinguish a single voice. What if a friend joined you? There would be a better chance that you both would hear similar sounds and agree on who spoke. However, in actuality, you and your friend would not hear exactly the same background noise, so trying to agree on what was said would be more difficult, but – as Lynch’s research shows – not impossible. This analogy is essentially the LIGO project and Lynch’s research problem.

Interpreting noisy signals is the core of Lynch’s research with LIGO: fast identification of a signal’s source so as to alert astronomers to point their telescopes at the right place – to catch a glimpse of the excitement! “Think of LIGO as two really big antennas,” Lynch says. Similar to our earlier voice analogy, data received by LIGO’s instruments must be shown to be a real signal, and a source for those signals must be identified. In order to determine whether the received data represents a signal, it must pass a series of tests. Initially, because of the large quantity of data over which to search, Lynch trims down the search-space by selecting high-activity areas with high-amplitude data. Secondly, “it has to be received by both detectors [at the appropriate time] and the signal has to look the same,” Lynch explains. Going back to the busy street, Lynch’s description of LIGO’s signal detection process is like waiting.
for moments when there is a loud outburst, then confirming that both you and your friend heard it, and that it sounded the same. Although this process determines whether the instrument received a signal, there is still the mystery of the origin of the signal. In his research, Lynch determines the origin of the gravitational wave given the information that we know about the signal—and sometimes the lack of information we know.

There are many methods for analyzing signals for which we have analytical solutions and models to determine its source, but Lynch’s research deals exclusively unknown signals. In order to get a better understanding of Lynch’s conditions, take our busy street analogy and imagine that rather than hearing a voice you hear a generic sound. Suppose you hear a noise that is a combination of a soprano and bass note from two singers. Your task would be to listen to the note and distinguish the source of the noise—the singers in this example—using your knowledge of vocal ranges and the singer’s voices. Ultimately, you and your friend want to decide which portion of the sound comes from each tone. This is done by comparing the received sound to each tone of the vocal range, quantifying their similarity to each, and adding them up to get an overall correlation of the signal for each range. Similarly, Lynch’s research compares the signal received by astronomical events to very generic templates: overlaying the original, received signal to the signal generated by each template to estimate their differences, and comparing each of the differences to get the best fitting templates from the set of generic templates. A larger portion of Lynch’s job is to write code that conduct all of this complex analysis, which then makes identifying and locating gravitational-wave sources much easier and faster.

Lynch’s research is focused on training computers to listen and interpret the sounds of the universe more effectively, through machine learning. Machine learning is taking characteristics of the signals that help us define the data as a signal or as noise. We then take the set of data we receive and label it as a signal or noise. From here, we give this training data to the computer, which allows the computer to develop models to predict whether data it receives is a signal or noise by creating a threshold range for each of these characteristics. Ultimately, we want to be able feed data to a machine and be given a quick confirmation of gravitational wave detection as well as its source and source’s location! Tools like those developed by Lynch will help to answer many of the puzzling questions of the universe, specifically the most confounding of them all—the beginning.

If we can automate the processes of recognizing a gravitational-wave event, it will allow us to hear these signals much faster and more efficiently. Lynch’s research has already made great impact on the field; some of his code and models were used in the first ever detection of gravitational waves. Lynch’s research is helping to open up conversation between the universe and man that will allow us to learn even more about it. Lynch explained that the majority of the purpose of his research is to study the sources of the gravitational waves of the early universe. Given the vastness of the universe, these relics of the past have been travelling for millions of years to tell us the secrets of the past and give physicists an idea of what the “climate” of the early universe was like. Lynch’s techniques for determining signal source and location will tell us what created these gravitational waves and where, constructing a map of the universe’s past, which may give us a look into its future. The prospects for astronomy and astrophysics are strong now and only getting stronger with this amazing research by Ryan Lynch and the MIT LIGO team.

Justice Mason graduated with a Bachelor of Science degree in aero/astro and physics from MIT in June. Since graduating, he works at NASA Jet Propulsion Laboratory. He has enjoyed his time at MIT, dancing with DanceTroupe and Ridonkulous, participating in the Undergraduate Research Opportunities Program, and developing his love of engineering and science.
It has long been known that baryonic matter, which make up stars, planets, and living organisms, contributes only a small fraction to the total mass of the universe. The rest is dark matter, a mysterious substance which has never been directly observed, but whose existence has been confirmed from its gravitational interactions with ordinary matter.
According to measurements of these interactions, the amount of dark matter in the universe is five times as much as ordinary matter, yet there is much to be learn regarding its properties. Greg Dooley, a graduate student at MIT, is running dark matter cosmological simulations to study how dark matter models affect the formation and evolution of clusters of galaxies in the universe.

Currently the most widely adopted cosmological model is the Lambda-Cold Dark Matter, called the ΛCDM model, which postulates that the universe contains a cosmological constant Λ, associated with dark energy, and cold dark matter. This model is simple yet effective in explaining many properties of the universe, such as the existence and structure of the cosmological microwave background, the distributions of galaxies, the chemical abundances of elements, as well as the accelerating expansion of the universe. However, there are problems yet to be resolved by the ΛCDM model.

One such problem is the cuspy halo problem, which is the discrepancy between simulations and observations of density distributions of dark matter halos (a component of a galaxy that envelopes the galactic disc and extends well beyond the edge of the visible galaxy). In simulations, the dark matter density profiles increase steeply at small radii (i.e. cuspy), whereas observations of rotation curves (the plot of orbital velocity as a function of distance from the center) of dwarf galaxies suggest that the profile is much flatter near the center. Another problem is the “too big to fail” problem, which again shows disagreement between simulations and observations. Cold dark matter simulations predict circular velocities of subhalos that are too high to be consistent with any known Milky Way satellites. Scientists propose different resolutions to help alleviate these problems, introducing baryonic phenomena such as supernova outflow, bursty star formation, or tidal disruption. Dooley, however, takes a different approach: he modifies the properties of dark matter to allow for non-trivial self-interaction.

In the ΛCDM model, the dark matter is hypothesized to be slow-moving compared to the speed of light (thus, cold), and interact almost exclusively through the gravitational force. Therefore, cold dark matter is collisionless – the interaction cross-section is so low that dark matter collisions, either with itself or with baryonic matter, are virtually non-existent. However, Dooley and his research group observe that, by prescribing a new type of dark matter with strong self-interaction (self-interacting dark matter), the cuspy halo problem and the “too big to fail” problem could be alleviated. Self-interacting dark matter will have a non-trivial probability of colliding with one another.
and scattering elastically. The scattering effect will be particularly strong in the central region, where the density is high, resulting in significant tidal dispersal and stripping of stellar masses, thus effectively reducing the central density of halos, resolving the aforementioned problems. Simulations by Dooley’s research group show that the density profile of self-interacting dark matter halo flattens out near the center (i.e. cuspless), strikingly similar to the actual observed profile of galaxies. As the density profile is reduced in the inner regions, the circular velocity profile of subhalos also drops and agrees with observations as well.

There are several ways to observationally test the hypothesis of self-interacting dark matter. Since the model predicts that ultra-faint dwarf galaxies will not have a core, astronomers could look at them and evaluate the claim. However, since ultra-faint dwarf galaxies are very dim – roughly 100,000 times dimmer than a typical galaxy like the Milky Way – they are very difficult to observe with sufficient details. Thus, the current data is sparse and inconclusive, but future progress in telescope technology is expected to solve the problem. A different testing method is to predict the number of satellite dwarf galaxies orbiting around a major one, and compare the figures with observations.

The idea of self-interacting dark matter was proposed in the early 2000s, and the initial simulations of self-interacting dark matter were carried out by Professor Vogelsberger at MIT in 2012. Recently, Dooley has been working with Professor Vogelsberger and Professor Frebel at MIT, Professor Peter at Ohio State University, and Dr. Jesus Zavala from the Dark Cosmology Center in Copenhagen, to run more simulations with increased details and resolution, as well as updated cosmological parameters measured by the WMAP and the Planck missions. Since the scale of cosmological simulations is very large, typically most simulations are dark matter-only, and ordinary matter is added accordingly, or ‘tagged’, toward the end. This approach helps to reduce the computational power required for the simulations, which take months or even years on a supercomputer. In the future, Dooley is hoping to add more baryonic interactions, such as hydrodynamics, as well as stellar formation, galaxy formation, supernovae, and active galactic nuclei feedback mechanisms, to the simulations. The inclusion of baryonic physics would produce more precise predictions as well as observational tests checking the validity of self-interacting dark matter. Nevertheless, Dooley comments, “The addition of baryonic physics would be very costly in terms of computational power... If a typical galaxy-scale simulation takes 2 months to run on a supercomputer, the equivalent time for self-interacting dark matter simulation would be 3 months. If you include hydrodynamics on top of that, the runtime would increase fourfold to 12 months.” Dooley is investigating and applying analytical methods that would reduce the simulation runtime, as well as trying to secure more computer nodes to run his simulations. “As it is a parallel code, the more computer nodes we have, the faster it is,” he said. At the same time, he expresses his hopes that advances in the field of computing would result in faster runtime of high-resolution detailed simulations.

Since dark matter interacts very weakly with electromagnetic radiation, it cannot be observed directly. Thus, computational simulations carried out by Dooley and his research group are essential to the advancement of the field. They produce predictions of effects by dark matter that could be tested by actual astrophysical observations, either validating or disproving certain theoretical cosmological models, bettering our knowledge of dark matter. Studies of dark matter properties is a field of unexplored horizons, and future progress in both computing and telescope technology will contribute to the joint effort by many physicists, theorists and experimentalists alike, to eventually discover the mysterious properties of the elusive yet prevalent dark matter.

Duy-Anh Doan graduated with a Bachelor of Science degree in physics and earth, atmospheric and planetary science at MIT. After graduation, he will attend Penn State to pursue a Ph.D. in astrophysics.
Superconductivity at room temperature has long been an unattainable goal for scientists and engineers working in the field of condensed matter physics. Although Heike Kamerlingh Onnes first discovered the effect of superconductivity in 1911, the critical temperature required to observe this effect was only 4.2K, which made its utilization impractical for many potential applications.
Since then, scientists have worked diligently to obtain materials that would exhibit superconductivity at higher temperatures.

It is still a mystery whether superconductivity at room temperature is actually achievable, but according to MIT graduate student Fahad Mahmood shining ultrafast lasers on thin-film superconductive materials could answer this long unsolved mystery.

In 1986 it was discovered that cuprates, which are crystals made of copper and oxygen, exhibit superconductivity at temperatures as high as 90K and this new family of materials were named high-temperature superconductors. Although this discovery facilitated many practical applications that were impossible with regular superconductors, the working principle of these new materials could not be explained with the BCS theory, which first explained the working principle of conventional low temperature superconductors and garnered a Nobel Prize in Physics for John Bardeen, Leon Cooper, and Bob Schrieffer (“BCS”) in 1972.

Free electrons in a material, which conduct electricity through their motion, collide with the neighboring atoms as they drift due to the applied electric field and this is why most materials show resistance to electrical current. However, according to the BCS theory, at fairly low temperatures free electrons in certain crystals can pair up and form “Cooper pairs” as the result of electron-crystal interactions, and these special pairs do not collide or interact with the neighboring atoms as the regular electrons do. Furthermore these Cooper pairs will form a collective group, known as a Bose-Einstein condensate, and they will move as a group in unity, without being affected by the neighboring atoms, or in other words without any resistance.

We can think of the electrons in a resistive material as single individuals dancing on the floor of a nightclub. As these singles try to move around, every now and then they will collide or interact with someone dancing on the floor and this will slow down their movement in the desired direction. On the other hand, we can imagine the group of Cooper pairs in a superconductor as a group of couples dancing in a ballroom. Although the ballroom will be packed with dancing couples, these couples will follow a specific choreography to move around without colliding with other couples. The group of couples will move in unity in a seamless way without any collisions as long as they follow the choreography. According to Schrieffer, one of the contributors of the BCS theory, the effect of low temperature superconductivity in certain crystals can be thought of as a special choreography of electrons when they form Cooper pairs and dance in unity. [1]

“However, the effect of high temperature superconductivity observed in cuprates can not be explained with the BCS theory,” Mahmood says. “Although we still don’t know how high temperature superconductivity exactly works, we think that phonons, magnons, or some other quasiparticle is probably responsible for it.”

Mahmood is working with ultrafast lasers and a
thin-film material called LSCO cuprate, which is a type of high temperature superconductor, to solve the mysteries of high temperature superconductivity. He explains that, by shining a very powerful laser pulse on the LSCO cuprate, superconductivity can be disrupted and some of the Cooper pairs, as energetic photons interact with them, can be separated into two different electrons. This is in principle similar to any phase change we see in our daily lives; if you apply an excess amount of energy to a cube of ice, either by heating or by shining a powerful laser pulse, it will melt into water. Just as the more ordered crystal structure of ice turns into the less ordered liquid form, the ordered group of Cooper pairs will become an unordered roup of electrons.

Mahmood is excited about what happens next. “Once the applied laser pulse ends, the superconductor will slowly return to equilibrium, which means that separated electrons will recombine to form Cooper pairs again. How exactly do these electrons bind each other and through what mechanism do they recombine into Cooper pairs? These are the questions that can give us important insights about the working principles of high temperature superconductivity and the good thing is they can be answered by our ultrafast optical techniques,” says Mahmood.

Besides disturbing the Cooper pairs and observing the recombination process, these ultrafast optical techniques can be also utilized to organize the electrons of a superconducting material in an interesting way called charge density waves. Charge density waves are sinusoidal distribution of electrons, similar to the water waves on the surface of the sea. This is an interesting formation, because in a regular material electrons form a uniform distribution, similar to the smooth surface of a lake. Even more interesting is the fact that charge density waves and superconductivity can coexist in the same material. That is to say, when a snapshot of the material is taken at a point in time using ultrafast spectroscopy, electrons could be observed in the charge density wave state, however in another snapshot taken shortly after electrons could be observed in the superconductivity state.

The observation that charge density waves and groups of Cooper pairs coexist in a superconductor has interesting implications for high temperature superconductivity. Although it is still unknown whether these two phases of electrons compete with each other at any time, researchers including Mahmood’s group are devising new experiments to understand the nature of interactions for these two phases. A recent experiment done by another research group at Max Planck Institute in Germany showed that by shining ultrafast laser pulses on a superconducting cuprate, the effect of charge density waves could be eliminated and they were able to get superconductivity at 250K for a very short duration of time. This is a very important step towards attaining superconductivity at higher temperatures and naturally raises the question: if charge density waves in a superconductor can be eliminated completely, can superconductivity at room temperature become a reality?

Mahmood thinks that if we can solve the mystery of high temperature superconductivity, it will provide us with the required information to engineer new materials that could exhibit superconductivity even at room temperature. High temperature superconductivity is one of the most exciting research areas in condensed matter physics, because if we can achieve superconductivity at room temperature, that would be one of the greatest feats of the human history. Practical implications of such an achievement would range from ubiquitous quantum computing and super-efficient data centers to lossless transmission of electrical power.

References:

Ahmet Musabeyoglu graduated from MIT this June with a Bachelor of Science degree in physics and electrical engineering. During his time at MIT, he enjoyed playing soccer, building electronics circuits, and watching a lot of movies.
Entanglement, the phenomenon where characteristics of one particle depend on another, has captivated physicists since Schrödinger first described it in 1935. Part of this interest stems from entanglement’s useful real world applications such as decryption and information transfer.
But before physicists use entangled particles to accomplish any of these tasks, they are focused on solving a more difficult problem: predicting whether particles are entangled in the first place.

On the surface, testing whether two particles are entangled or not – what physicists call separable – seems easy. For electrons with spin, a quantum characteristic that is either up or down, measuring the spin of two entangled electrons will always yield one electron with spin up and one with spin down. For separable electrons, some measurements would yield both electrons with spin up or both with spin down, proving that the electrons were originally entangled. But while determining whether two electrons are entangled after measuring them is simple, predicting whether more than two electrons are entangled without measurement is incredibly hard.

At MIT’s Center for Theoretical physics, graduate student Anand Natarajan is exploring the quantum separability problem, called QUSEP, by searching for faster and more accurate algorithms to determine whether particles are entangled or separable. Originally interested in particle physics while completing his undergraduate degree, Natarajan took theoretical computer science classes before being introduced to the fields of quantum information and complexity. “Eventually I realized there’s this field where you can think about complexity theory and physics,” he says. “That’s what led me to be interested in quantum information.”

But unlike the fields of classical information and computing, which today require testing and implementation on physical computers, quantum information and computing is far more reminiscent of theoretical physics in the early 20th century. When tackling problems such as QUSEP, “It’s mostly pen and paper or on the blackboard,” says Natarajan.

At its most abstract level, QUSEP can be thought of as the problem of separating the continuous “region” of all possible quantum states into two regions representing unentangled and entangled states. Imagine a large pasture of cows, your unentangled states, with a cluster of sheep, your entangled states, in the middle and the task of placing a fence around the sheep so as to completely separate them from the cows. From a high vantage point, you could imagine that it is quite easy to place a fence that completely separates the sheep from the cows, but the quantum world is not
so kind. Grass has grown far above the animals, requiring you to check each animal before the fence is placed. By analogy, an algorithmic solution to QUSEP would efficiently check and separate the sheep from the cows, or the entangled states from the unentangled states.

But there is a catch that makes Natarajan’s search for more efficient algorithms far more complex: QUSEP was conjectured in 2003 to be a member of a class problems called NP-hard. While classical computers can quickly check the solutions to NP-hard problems, computers cannot quickly find the solutions themselves. This distinction has far-reaching consequences for the problems theorists can solve efficiently. Since the time it takes classical computers to solve problems like QUSEP scales exponentially, even the fastest computers may not find a solution in a human lifetime. While QUSEP’s membership in the NP-hard class is still debated, complexity theorists doubt classical computers will ever be able to solve QUSEP easily.

This revelation presents a challenge to researchers like Natarajan who are searching for efficient algorithms to solve QUSEP. While researchers must accept the possibility no efficient classical algorithms, they can still try to optimize inefficient algorithms to study QUSEP. Towards this end, Natarajan has developed an algorithm around the sum-of-squares hierarchy along with fellow researchers Aram Harrow and Xiaodi Wu.

The group’s algorithm reduces QUSEP to an optimization problem, which is like finding the highest peak in a mountain range. The key development of Natarajan’s group was the inclusion of mathematical constraints that allowed their algorithm to find solutions faster than previous algorithms. “We used this miraculous result from some people in the math literature,” says Natarajan. “When you add these special constraints… this hierarchy converges at a finite level to the exact value.” In addition, Natarajan’s group examined the algorithm’s performance when very close to the boundary between the region of entangled states and the region of unentangled states and found it as precise as previous algorithms.

While possible solutions to QUSEP are fascinating in their own right, Natarajan’s research into QUSEP also brings physicists closer to understanding a complexity class called QMA, or quantum Merlin Arthur. QMA is the set of problems for which a quantum computer can only quickly check solutions rather than quickly finding the solution itself. So far, complexity researchers believe that there is a difference between QMA(1) and QMA(2), the classes where a quantum computer verifies possible solutions to one or two problems respectively.

Natarajan likes to think of the difference between QMA(1) and QMA(2) as interrogations of one or two witnesses aided by a quantum computer that attempts to determine whether they are lying or not. “If I want to interrogate one witness, they can come up with whatever lie they want to tell”, says Natarajan. “But if I have two witnesses who are not allowed to communicate, it’s much harder to coordinate their lies.”

Remarkably, if Natarajan’s group is able to find an efficient quantum algorithm to solve QUSEP, they will also prove that there is no difference between a quantum computer interrogating a single person or two people, an exciting discovery in the field of quantum information. While special cases of this problem have been proven, researchers are still searching for a general solution. “People have gotten tantalizingly close to this,” says Natarajan.

At its core, Natarajan’s research is just as focused on identifying the questions that we will never answer efficiently as it is on answering questions that we can answer. Problems like QUSEP and complexity classes like QMA form distinct limits on our theoretical understanding of physics. Even if a time efficient QUSEP algorithm is proved impossible, that failure would yield significant advances in physicists’ understanding of the differences between QMA(1) and QMA(2). But for the time being, “QMA is much less well-understood,” says Natarajan, leaving the deceptively simple separability problem still unsolved. 

Connor Popik is a rising senior majoring in physics and economics at MIT. After graduation he hopes to eventually pursue a career that links biophysics and healthcare economics at a biotech company.
Every day, across forty-three orders of magnitude in distance scales, scientists are making discoveries that affect society. To support sound public policy about the issues which arise from this research, it is essential for physicists to engage in the public debate. MIT 8.226 explores some of the questions that our present scientific achievements raise, both for our own community and for the public at large. By considering topics as diverse as climate change and nuclear nonproliferation, this class makes the case that physics is a necessary part of the national discourse.

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PROFESSOR J.M. CONRAD