inside the Perimeter

fall/winter 2018/19

Quantum quandaries

Musical neutron stars

People of PI

Lasers!

... and much more

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Inside the Perimeter

Editor
Natasha Waxman
nwaxman@perimeterinstitute.ca

Managing Editor
Tenille Bonoguore

Contributing Authors
Tenille Bonoguore
Erin Bow
Dan Falk
Colin Hunter
Stephanie Keating
Neil Turok

Copy Editors
Tenille Bonoguore
Mike Brown
Colin Hunter
Stephanie Keating
Kelly Pedro
Natasha Waxman

Graphic Design
Gabriela Secara

Photo Credits
AdobeStock
istockphoto
NASA
Gabriela Secara

Cover Watercolors
Kaća Bradonjić
Front: "Steven Abel, 'Progress in constructing an Asymptotically safe Standard Model, 2'"
Back: "Masatoshi Yamanda, 'Asymptotically safe gravity and electroweak scalegenesis'"

Inside front cover
"100 Closest Stars (2016)"
by Lucy Pullen

This sculpture, installed on the feature wall at Perimeter, represents the volume of 100 closest stars, based on open-source data from NASA. The forms are made with voronoi geometry, in collaboration with Stuart Lynn, head of research for CARTO in Brooklyn, NY.

Inside the Perimeter is published by Perimeter Institute for Theoretical Physics.
www.perimeterinstitute.ca

To subscribe, email us at
magazine@perimeterinstitute.ca

31 Caroline Street North,
Waterloo, Ontario, Canada
p: 519.569.7600 | f: 519.569.7611

IN THIS ISSUE

THE BEST IS YET TO COME

I have been fortunate to serve as Perimeter's Director for a decade. It's been the opportunity of a lifetime, both challenging and exhilarating, and an enormous privilege to lead such a dedicated and willing team. Together we have built a faculty, a community, and a culture which is, I think, uniquely forward-looking and ambitious. We encourage each other and, above all, our young people to be unafraid of seeking answers to the most difficult questions. Together, we are creating a new kind of research institute for the world. I use the present tense because I believe our work has only just begun.

When I was recruited here, Waterloo was still relatively unknown as a world centre for physics. That much has changed. This year's Nobel Prize win for Donna Strickland at the University of Waterloo, for the extraordinary discovery she made as a PhD student of chirped pulse amplification in laser physics, is a huge boost for our collective efforts. We were likewise honoured by the visit of Jocelyn Bell Burnell, winner of this year's Special Breakthrough Prize for her discovery of pulsars, also made as a graduate student. Characteristically, Jocelyn donated her prize to support PhD students from underrepresented groups. It was a very special occasion to have Donna and Jocelyn join us together to celebrate their achievements, and to announce a new series of named postdoctoral fellowships before Jocelyn's public lecture. (See page 6.)

Young people are the future, in physics as in every other field. Their freshness and lack of prejudice bring new energy and critical thinking. It is vital that we continually re-examine and challenge the foundations of physics. Youth and diversity provide our greatest source of vitality in doing so.

It's no a coincidence that both Donna and Jocelyn made their breakthroughs at a young age. Beginners do not see the barriers from which others shy away. A first-year graduate student can ask a question or invent a new way of doing things that sparks a revolution.

One of my first acts as Director was to open Perimeter's doors to students. The Perimeter Scholars International (PSI) master's program commenced in 2009. We set out to recruit extraordinary students worldwide, to expose them to theoretical physics' full sweep, and to encourage them to become young researchers. PSI has become, by any metric, the world's most sought-after and successful master's program in theoretical physics.

Our postdoctoral program is another flagship effort. Just as others increasingly move towards project-based postdocs, we do the opposite. Here, postdocs are encouraged to set their own course, to work with whom and on what they may wish. Our new named fellowships – seven so far announced – are a nod to past greats and an encouragement to the holders. Perimeter is proud to host the largest community of independent postdoctoral fellowships in the world.

We take risks on unusual people. We have admitted students straight out of high school into PSI and appointed a faculty member straight out of his PhD. Not everyone needs to be precocious, but we should be open to those who are. We have hired pure mathematicians to interact with and enrich our physicists. We have hired specialists in advanced data analysis to deal with the torrent of new data from probes of the cosmos. It is very exciting to see those gambles now paying off: in Canada's new CHIME radio telescope, in the rapid advances of multi-messenger astronomy, in new searches for dark matter. In all of these fields, Perimeter is emerging as a world leader.

Perimeter's faculty have so far won five New Horizons prizes, the largest awards for young physicists, given by the Breakthrough Foundation (whose name was inspired by a conversation here at Perimeter). The founder called me a year ago to say, "How do you do it? The young people you hire keep winning our prize!"

The recipe is simple: look below the horizon for original, passionate, pioneering young scientists. Provide them with the time and freedom and support they need to focus on what they want to focus on, to explore unconventional avenues with vision and undivided intensity.

As we all should. Because, amazing as it seems after centuries of discoveries that transformed society, we have barely scratched the surface of physics and what it offers us all.

We need to be more effective and efficient not only in pursuing breakthrough discoveries but in communicating the magic and wonder of understanding the universe to everyone. There are vast numbers of young people whose talents are lost because they were never fostered. Perimeter's dual mission – of research advances and sharing the thrill of them with millions of students and the public – makes it a positive force for progress in these troubled and anxious times.

Our outstanding Educational Outreach team has organized spectacular festivals – from Quantum to Cosmos in 2009, to Convergence in 2016, to Innovation150 which travelled right across the country in 2017.

Each has been a creative feast inspiring students, teachers, and curious minds of all ages. It isn't too much, I believe, to say that Perimeter plays a part in defining Canada as a place where new ideas are welcomed in an atmosphere of internationalism, openness, enterprise, and hope for the future.

What drives us is our unbridled curiosity and appreciation of the extravagant beauty and simplicity inherent in nature. By sharing the joy of discovery and the opportunities it brings, by opening access to talented people from everywhere, Perimeter is showing the world what is possible.

Over the past decade, Perimeter has grown into a significant institution. As we grow up, we should hold on to our sense of fun and excitement while we reach for the stars.

What a brief and wonderful trip it's been! And we're just getting started.

– Neil Turok

Nobel Prize winner Donna Strickland, Perimeter Director Neil Turok, and Special Breakthrough Prize winner Jocelyn Bell Burnell.

DEPTH OF VISION

Pioneering astrophysicist Jocelyn Bell Burnell isn't one to stand back from a challenge, whether it involves analyzing data, tackling sexism, or leading change within science itself.

Jocelyn Bell Burnell has an unusually acute talent for noticing the unnoticed. When she was a young child, her family took in refugees from Hitler's Europe. There would be four or five of them at a time, learning English and helping out on the family farm in Lurgan, Northern Ireland.

The refugees would come and go, their lives rendered flotsam in a world riven by war. But while they might have felt like forgotten people, the small girl in their midst noticed them, and remembered.

By 1967, that girl had become a graduate student in Cambridge, studying her beloved radio astronomy. After spending two years helping build a radio telescope, it was her job to pore over kilometres of paper charts it generated, looking for evidence of quasi-stellar objects, or "quasars."

One day, she noticed something on the readout: a bit of "scruff" where one of the lines on the chart briefly jumped. It wasn't the right readout to be evidence of a quasar, so she moved on. Further along the chart, the line bumped up again. Something in her mind clicked. "I've seen this before," she remembers thinking. She went back along the chart, found that first bit of "scruff," and compared them. They were the same.

Bell Burnell had just uncovered the first evidence of pulsars, rotating neutron stars that emit a beam of radio waves that sweep through space, rather like how a light house beam sweeps through the sky.

She would go on to find the first four pulsars and to publish the first evidence of them as an appendix on her PhD thesis. (Her supervisor told her it was too late to switch the topic of her thesis from quasars to pulsars. "It's probably the most read appendix of anybody's thesis," she quips. That supervisor would, controversially, go on to share the 1974 Nobel Prize for his "decisive role" in the discovery of pulsars.)

But what should have been the launch of her career in radio astronomy actually turned out to be its end, because she had an engagement ring on her finger.

In Britain in the 1960s and 1970s, it was unthinkable that a married woman would have a career. At least, it was unthinkable to those whose minds were closed to it. Bell Burnell's mind, as usual, was not.

With a Cambridge PhD in hand and the discovery of pulsars to her credit, she wrote "begging letters" to observatories and universities, seeking whatever job she could find in whatever town her husband was working. "I didn't find it acceptable, to be honest," she says during a recent visit to Perimeter to deliver a public lecture. "It was pretty galling."

When they had a son, she hit yet another wall. "The attitude in Britain then was that – indeed, it was 'proven' apparently – that if mothers worked, the children were delinquent." That meant that there were no childcare facilities, because that was seen to encourage mothers to work. "It was extremely difficult," she adds.

Away from extended family and having no societal supports, solutions were usually an improvised mix of part-time work and ad-hoc child minding from people in whatever area they were living in. And so it went for 18 years.

"I was pro-active as far as I could be. I would get some fairly lowly job in a place near where my husband worked, and I would work at that as well and as intelligently as I could, and would work my way up the hierarchy."

And then they'd move. "Do you have a game of snakes and ladders here? You climb a ladder, slide down a snake, climb a ladder..."

Some unexpected benefits emerged from this patchwork of a career. Bell Burnell discovered early on that she was good at managing groups of people. She worked in public relations, as an international liaison, in the tech department of a research project, and teaching undergraduates. And she ended up working in almost every wavelength in astronomy.

"Each time we moved, I had to learn a new kind of astronomy, which in one sense is grossly inefficient, but also extremely interesting and gives you a great breadth of understanding," she says, before adding with a wry smile: "Although it makes you far too useful on committees assessing proposals."

All along, the radio astronomy community kept her in the loop on her true love: pulsars.

Now in retirement from active research, and also now a Dame Commander of the Order of the British Empire, Bell Burnell remains closely tied to both the latest research and to the need to keep advocating for diversity in science through programs like Athena SWAN, a gender-equality charter for UK universities that she helped start in 2005.

She keeps a close watch on science and society, engaging both with her trademark humour, keen-eyed precision, and "pig-headed" determination to call out inequality when and where she sees it. While she never spoke against the Nobel going to her supervisor – at the time, students were not included in Nobel citations; that changed after the public uproar over Bell Burnell's exclusion – the eminent physicist refuses to stay quiet about the structural issues that continue to prevent people from reaching their full potential.

"There aren't many people who have been through what I have been but are in a secure enough position that they can talk about some of these issues," she says. "I think people need to know."

It's not just talk, either. This year, Bell Burnell received science's richest award, the Special Breakthrough Prize in Fundamental Physics. Almost immediately, she announced that she would donate the $3 million US cash prize to support research scholarships administered by the UK's Institute of Physics, to be given to under-represented groups. That will include women, but it will also include ethnic, racial, and socio-economic minorities.

"I hope also some refugees," she adds. "One of the things that really struck me is that some of the first refugees out of Syria were people like pediatricians: very, very highly qualified people.

"I would imagine there would be some people who have done an undergraduate physics degree, a bachelor's physics degree, who are bright enough to do research."

As Bell Burnell knows all too well, something easily overlooked can actually turn out to be truly transformational. One just needs to know how to see it.

– Tenille Bonoguore

Watch Jocelyn Bell Burnell's Perimeter Public Lecture on Perimeter's YouTube channel and at
www.insidetheperimeter.ca/video/public-lectures

NEW NAMED FELLOWSHIPS FOR YOUNG RESEARCHERS

Perimeter Institute has introduced seven new postdoctoral fellowships. Each is named after an exceptional researcher whose work epitomizes the promise and potential of early career scientists.

The fellowship namesakes are:

Francis Kofi Allotey, a Ghanaian mathematical physicist who made pioneering contributions to X-ray nuclear spectroscopy, and who led the development of physics in Africa.

Jocelyn Bell Burnell, a Northern Irish astronomer who discovered pulsars and is a passionate advocate for minorities in science.

Yvonne Choquet-Bruhat, a French mathematical physicist who proved that Einstein's famous equations for gravity have solutions.

Stephen W. Hawking, a British cosmologist whose work on gravity shaped modern cosmology.

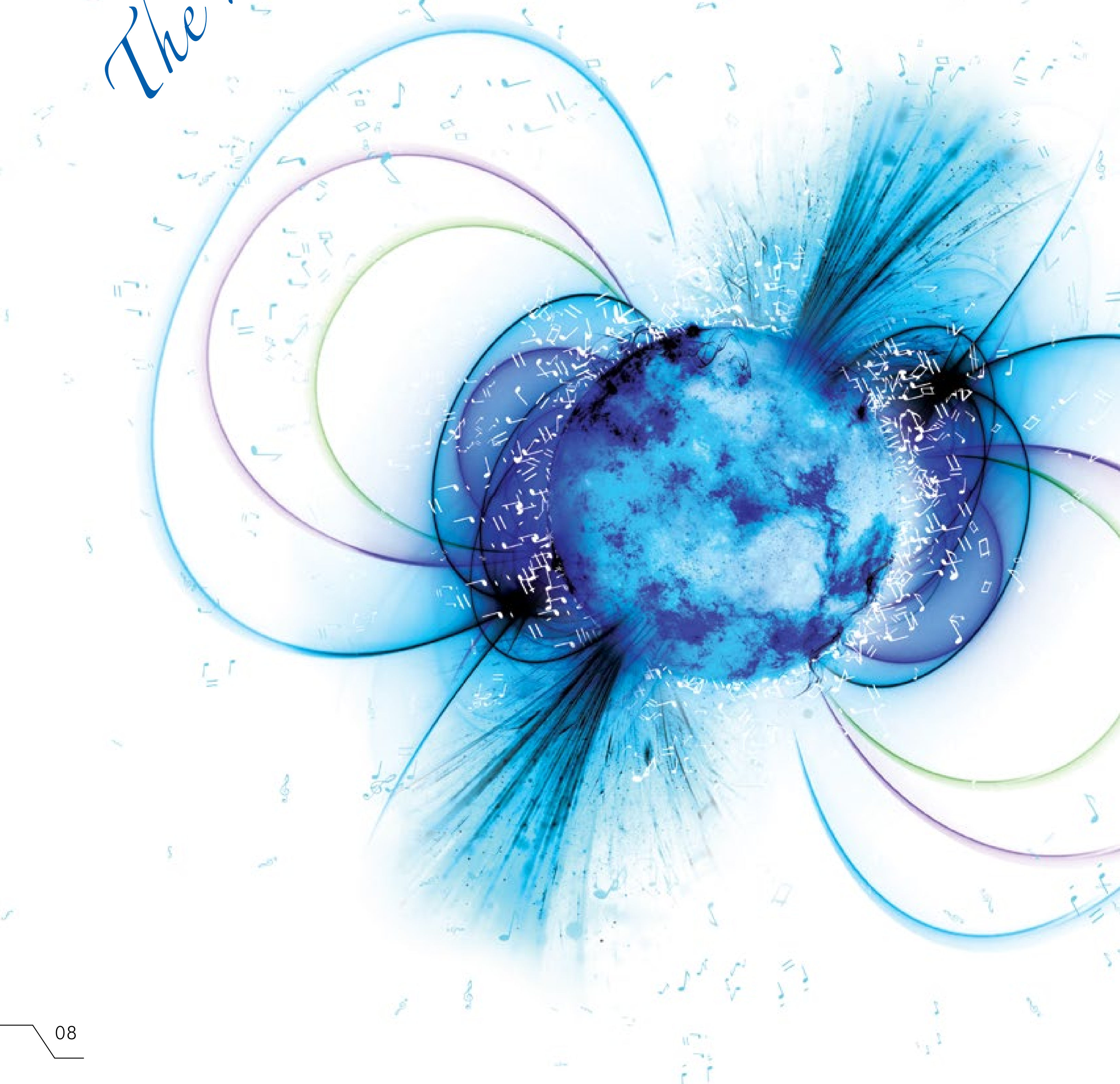
P. James E. Peebles, a Canadian-American cosmologist at Princeton who pioneered many aspects of modern cosmology including the origin of the elements and the formation of galaxies.

Chien-Shiung Wu, a Chinese-American nuclear physicist whose discovery of the violation of parity symmetry in the decays of atomic nuclei is a cornerstone in our understanding of the weak interactions.

Yakov B. Zel'dovich, a Belarusian scientist who made extraordinary contributions to many areas including cosmology, physical chemistry, and astrophysics.

Find out more at
www.perimeterinstitute.ca/about/careers

The music of neutron stars



Research reveals a new class of neutron star oscillation frequencies that are not predicted by general relativity.

What is the sound of a pulsating neutron star? The answer could reveal a lot about the nature of gravity.

In one theory of gravity, the sound is a high-pitched D note, just one key past the end of a standard piano. But under general relativity, the tone is markedly higher. If either of these tones is one day "heard" by gravitational wave detectors, it could have repercussions for our understanding of gravity.

The frequencies are put forward in research by Perimeter Institute postdoctoral fellow Nestor Ortiz and collaborator Raissa Mendes, from the Universidade Federal Fluminense in Brazil.

In their paper, published in *Physical Review Letters*, the pair test two theories of gravity: the reigning gold standard, general relativity, and a slight modification to general relativity, known as scalar-tensor theory.

Scalar-tensor theory uses a mathematical object called the metric tensor to describe spacetime. It then adds another component called a "scalar field" (a function that assigns a numerical value to each point in spacetime, though the physical interpretation depends on the context) that affects the interaction between matter and spacetime.

The researchers modelled neutron stars within each theory. The extremely compact nature of neutron stars, which pack up to three times the mass of our sun into a volume with a diameter of about 20 kilometres, make them ideal laboratories for testing how gravitational theories fare in "strong gravity" environments.

They gave each star a virtual nudge (i.e. modelled what would happen if the system was perturbed) and, using independent numerical and analytical methods, calculated the resulting frequency of vibrations. The process is akin to striking a tuning fork and listening to the note that it makes.

They discovered that the stars in scalar-tensor theory sing with a set of frequencies completely different – and, importantly, completely distinguishable – from those predicted by general relativity. For gravitational wave detectors, the two signals would be as different as a soprano voice is from a bass. "The interaction of these two fields [the metric tensor and the scalar field] is what makes these oscillation modes emerge," Ortiz says.

Given that this only emerges in scalar-tensor theory, detection of such oscillations would show that general relativity needs modification. "It could be the case that, in the interior of neutron stars, the theory still needs some modification in order to explain phenomena that we haven't observed yet," Ortiz notes.

Aside from the new class of oscillation frequencies, there are other signatures of the theorized scalar field that gravitational wave detectors can seek. Stars with an active scalar field will radiate gravitational energy more quickly than those without. "They also have different properties when they're in a binary system, so that leads to different predictions that we can test using gravitational waves," says Ortiz.

It may be some time until the observational verdict is in. Although current detectors are sensitive to the frequencies in question, researchers still have to work out the specific signatures to look for. In the meantime, Ortiz and Mendes have created audio clips to demonstrate what the stars would sound like to the human ear.

While not particularly melodic, the difference between the two is clear. In general relativity, the neutron star emits a high-pitched whine. In scalar-tensor theory, the star hums at a high-pitched D note, one tone above the highest note on a standard piano.

"It's almost there," Ortiz says. "I would have loved to have it on the piano, so I could hit a key and say, 'this is how a star sounds.'"

– Stephanie Keating

Listen to the different gravity sounds on Perimeter's YouTube channel: www.youtube.com/pioutreach

CHARTING A COURSE FOR GREATER INCLUSION

When it comes to women in physics, Canada is roughly on par with its peers, which is to say that women are in the minority at all levels of physics. Look at socio-economic and racial diversity, and the results are even more bleak.

In her new appointment as Perimeter's first Equity, Diversity, and Inclusion Specialist, Shohini Ghose wants to use data and discussion to tackle what is proving to be a pernicious challenge.

Ghose, who is also a professor of Physics and Computer Science at Wilfrid Laurier University and the director of the Laurier Centre for Women in Science, sat down with Inside the Perimeter *to discuss this new role.*

Inside the Perimeter: You want to bring conversations about diversity into the open. Why?

Shohini Ghose: I want to make it as normal as going to a blackboard and writing some equations. Let's go to a blackboard and look at the latest data on inclusion. We know that diversity helps with improving performance across the board in many cases; physics is no exception. If there are people who don't feel like they are able to perform at the level they could, or if they feel like there are some stressors to deal with, that hurts physics.

The goal is to find a way where everybody's performance is at the max. The bigger question is whether people are aware of those challenges. I think there is a broad assumption that things are fine and women have equal rights: if they choose to do physics they can. Perhaps there is not enough appreciation for the fact that it's not a level playing field.

Inside: How do you explain that to someone who hasn't experienced such challenges?

SG: My role is not to explain anything to anybody! It's about facilitating conversations and building an open environment where you are able to come to it on your own. Different people come to these kinds of difficult discussions in different ways. Real change happens when the question itself becomes normalized.

Inside: Your appointment coincides with a broader Canadian push to explore diversity in science. NSERC (Natural Sciences and Engineering Research Council of Canada), for example, is looking at starting a version of the Athena SWAN program [a gender-equality charter for UK universities] here. How does Canada currently compare to other countries in terms of diversity in physics?

SG: I've seen research showing it's on par with a lot of other English-speaking western nations. The most recent numbers I saw put the faculty proportion around 18 percent, which is low. There's been a slow increase over the years, but there's basically a flat line when it comes to women who are not white. It's a little bit discouraging.

Different countries have different cultural contexts. We have to think about the Canadian context and figure out what is the environment for women, not just when they reach institutions like PI but well before that, when they start in school, why are they choosing certain majors and not others. It's hard because we don't usually collect these numbers in a broad way. That's part of what Canada has to do better, I think: get numbers and understand the context better and see what is specific to Canada.

Inside: I was recently watching a talk by Jocelyn Bell Burnell and she said it's time to stop inclusion efforts for women and instead bring science to women. Where are we on that spectrum between "fix the women" and "fix the system"?

SG: Things like our maternal leave policies are aimed at fixing the system; policies around training for unconscious bias, conversations around gender equity and harassment policies, these are about fixing the system rather than trying to make the women adapt to a broken system. But let's be clear, those are top-down policies coming from the leadership.

The "fix the women" piece is definitely big in terms of mentoring workshops and outreach to girls. I do agree with Jocelyn Bell Burnell: long-term, this is actually more damaging than it is helpful. Can we just stop all the mentoring and stop all the support? No way. We need the Band-Aid until it is no longer necessary and we can actually address the health of the entire body. We need the Band-Aids for now.

There's also got to be bottom-up initiatives around conversations and speaker series and one-on-one sessions. That's sort of a missing piece, that cultural conversation.

Inside: Doesn't it get exhausting for under-represented people to always be explaining why they're under-represented?

SG: Yes it is. It's a double whammy: on one hand you're under-represented and on the other hand the burden of fixing the problem is on you. It's like going to hospital with an injury where you have to do all of the surgery and the healing. But a lot of social science research shows that real social change happens not when everybody buys in, but when a certain minimum number do. You reach a critical mass, kind of like physics, and suddenly there is a chain reaction. It typically is around maybe 25 percent to 30 percent of the population.

Inside: Really? Is that all?

SG: Yeah, that's why I'm hopeful: 25 to 30 percent is kind of doable. Doesn't that make you happy? This is how you convince people it's not that impossible. Think about the LGBTQ movement. It's possible to shift perceptions. This gives me hope.

Inside: Do you expect physicists to be open to exploring these issues?

SG: I think that the great strength of physicists is they tend to be open to new ideas. You have to be as a physicist. We all have our initial unconscious bias reactions and we like the familiar and we don't necessarily like change; but if anybody can change I think it's physicists. They're always adapting to new ideas anyway. Here's a new idea, go look at the data, test presumptions, be skeptical, if you don't believe it, prove it wrong; but at least engage with it.

This is an issue that has been around for decades, so I'm not claiming that we're going to fix this in a couple of years. It's a starting point. PI could be a leader in this area. PI is uniquely situated because it's not quite a university, it's not an industry: it's a non-profit. It's got this unique position to be able to use its very high profile as an institution to build change that works and be that shining example.

– Tenille Bonoguore

THE QUANDARY AT THE HEART OF QUANTUM PHYSICS

Just because a theory works, doesn't mean we understand it, writes Dan Falk.

We're five minutes into the "Foundations of Quantum Mechanics" conference at Perimeter, and one of the organizers, Lucien Hardy, is talking about Isaac Newton. I consider this a stroke of luck, as I have some understanding of Newtonian physics and just might be able to follow along. Inevitably, the discussion among these 20 or so deep thinkers will turn to the intricacies of quantum mechanics, and when that happens I will be on shakier ground. But for now, Newton.

In 1687, Newton published his *Principia*, laying out his laws of motion and his theory of universal gravitation. Hardy, a physicist at Perimeter, notes that the landmark book was initially met with skepticism. The law of gravitation, in particular, puzzled readers. In Newton's theory, two bodies attract each other even if they're far apart. Whatever "gravity" is, it seemed to operate instantaneously over empty space. Scientists and philosophers – in Newton's time, there was hardly any distinction between them – figured that for object A to have an effect on object B, they either had to be touching or there had to be some sort of physical stuff in between A and B to mediate the force.

And yet, Newton's theory *worked*. In the decades following its publication, the ideas that he set down in the *Principia* were spectacularly confirmed, again and again. (A classic example involves the orbit of what we now call Halley's Comet. Astronomer Edmond Halley used Newton's laws to predict that a bright comet seen in 1682 would return in 1759. It did, though Halley didn't live to see his prediction borne out.)

What do we do when a theory is successful and yet runs counter to our intuitions? In the case of Newton's law of gravity, we had to wait a couple of hundred years. The tension was eventually resolved when Albert Einstein developed his general theory of relativity, in which gravity is seen to act not instantaneously but rather in a finite time, as distortions in the fabric of spacetime ripple across space. Newton wasn't wrong – it's just that Einstein's theory is more complete, and presents a more satisfying picture of how things work. (Indeed, when gravitational fields are weak, Einstein's equations become Newton's equations.)

Hardy argues that the analogy could be useful as we try to make sense of quantum mechanics. Quantum mechanics is an extraordinarily successful theory; it's given us everything from lasers to semiconductors, and some of its predictions have been confirmed to 11 decimal places (or perhaps 14, depending on how one counts them). We have managed to create astoundingly advanced technologies by following the very precise rules offered by quantum mechanics.

And yet, when followed through to its logical conclusions, quantum theory paints a profoundly weird picture of the universe: a universe where probability reigns, where we can barely say what things are actually made of. Some physicists feel we just need to get used to that weirdness; others hope that beneath the layers of weirdness is something more intuitively understandable, something closer to the sort of physics that ruled from Newton's time to Einstein's.

As I heard repeatedly during the week-long conference, it is far from clear what quantum mechanics is actually telling us about the world.

Hardy elaborated when I sat down with him between sessions. He drew a contrast between quantum mechanics and general relativity. The latter, he says "has a clear ontology" – in other words, we know what its equations are describing, in physical terms. "Whereas in quantum theory, that isn't the case," he says. "Or at least, there is no agreement on what the ontology is."

It's perfectly clear what the mathematical framework – the "formalism" – of quantum mechanics is, says Jonathan Barrett, a physicist and information theorist at Oxford. "We don't tend to disagree very much on the actual predictions and the actual experiments that we can do." But what does the math refer to? Does quantum mechanics encompass the *information* that we have about something? Or is it about the "real stuff that's actually there"? We just don't know, Barrett says.

Working with probabilities

At the heart of quantum mechanics lies a peculiar entity known as the wave function. Physicists can use the wave function to work out, say, the probability that a certain particle will be found within a certain region of space. The equations of quantum mechanics dictate how the wave function evolves. So far, so good. But why does the theory deal only in probabilities? Here, opinions diverge.

Depending on which "interpretation" of the theory you subscribe to, you might conclude that quantum mechanics is a theory of knowledge rather than of things; a theory requiring multiple universes; or something else altogether. Along the way, we get the famous "paradoxes" of quantum mechanics, like quantum superposition (in which a system is in two states at once, like Schrödinger's famous cat) and quantum entanglement (in which the properties of two particles can be correlated even though they're far apart and no signal has passed between them – what Einstein described as "spooky action at a distance").

Paradox may not be quite the right word for these phenomena; they may simply be features of the universe that we need to get used to. But they are certainly puzzling.

A good first step would be to understand what, exactly, the wave function *is*. "As a mathematical object, we're clear what it is – it's a vector in a mathematical Hilbert space," says Barrett. In other words, it's an abstraction, a mathematical entity that can be used to calculate probabilities. If you want to work out the chances of finding an electron between this point and this other point, the wave function is your friend. "But the question is, what does it refer to? What's it describing? What does it correspond to?"

Physicists have generally taken one of two approaches to handling that question, Barrett says. There are those "who take the wave function to be a part of the reality – some kind of real, physical wave that evolves – and those that take it to be a description, in some sense, of someone's information."

In the 1920's, the Danish physicist Niels Bohr, together with his young German colleague Werner Heisenberg, worked out what we now call the Copenhagen Interpretation of quantum mechanics: the idea, roughly, that the theory only describes what we are able to say about a physical system, not the system itself. A wave function describes a quantum system as existing in a superposition of states; when a measurement is made, the wave function "collapses" and a single value is observed. For example, when we measure an electron's spin, we might find it to be spin up or spin down. Before the measurement is made, however, we cannot be definitive; we can only say that it's in a superposition of the two states.

We can use the theory to work out the probability that *this* or *that* outcome will be measured, but not to predict outcomes of individual instances of experiments. Of course, probabilities aren't unique to quantum theory. Doctors, for example, tell their patients the probability that they'll have a heart attack or stroke within a certain time, but can't make more precise predictions. In quantum mechanics, though, it seems to be probabilities all the way down; they seem to be inherent in the theory itself.

For decades, Copenhagen was the most commonly accepted interpretation of the theory. But critics sometimes derisively call it the "shut up and calculate" interpretation (a phrase usually attributed to physicist David Mermin). At the Perimeter conference, I sensed little love for Copenhagen; over lunch, someone described it as "inconsistent and incoherent." Steven Weinberg, the Nobel laureate physicist, once wrote that if one adopts Copenhagen, one "rejects quantum mechanics altogether as a description of reality."

The interpretation also draws a distinction between the observer and the thing being observed, without ever saying where this boundary is or why it exists. This leads some to speculate that human beings, or perhaps conscious minds, are an essential part of the theory, since it is we (or our minds) that do the observing. This, Weinberg argues, represents a move away from the kind of science we've embraced since Darwin – a way of understanding humans as a part of nature, not as something separate and mysterious.

The conflict between interpretations

But if Copenhagen isn't the way to go, what is? Quantum mechanics has, by now, a notoriously large number of competing interpretations. Of these, perhaps the most provocative is the Many Worlds Interpretation (MWI), first put forward by Hugh Everett back in the 1950s. According to MWI, when a quantum event happens, *all* of the possible outcomes happen, each in a separate universe. At the Perimeter conference, the strongest proponent of the Many Worlds view was Israeli physicist Lev Vaidman.

Vaidman believes that, with MWI, the paradoxes of quantum mechanics disappear. Consider the probabilistic nature of the theory: in MWI, this can be seen as an illusion of perspective, Vaidman says. To any individual observer, only one outcome of a quantum measurement is seen and the equations of quantum mechanics can be used to work out the probability of seeing one particular result or another. There are no probabilities; everything simply happens, somewhere.

But not everyone is ready to climb onto the MWI bandwagon. Barrett, for example, says that MWI doesn't quite do away with probabilities as tidily as Vaidman believes. Another objection is more philosophical, involving the notion of the "self." If MWI is to be taken seriously, we have to accept the idea that each of us exists many times over across this multitude of universes.

At one point during the conference banquet, Hardy stood up and said, "We've got to change the laws of physics, and nothing else will do!" Quite a few people banged on their tables to indicate agreement. He went on, "The reason we have to come up with a theory of quantum gravity is to prove that Lev is wrong," adding wryly, "and my biggest fear is that we'll end up doing the opposite." Vaidman smiled.

The conference came to an end, but the quest to make sense of quantum theory continues. Everyone, it seems, has a different intuition about how the journey should proceed and where it might end.

After discussing Newton, Hardy moved on to Johannes Kepler. The German mathematician came up with empirical laws that describe how planets move: the three laws of planetary motion. Kepler's laws were accurate – you could use them to predict planetary movements with precision – but they seemed ad-hoc. Where did they come from? This was only clarified when Newton came up with his laws of motion and gravity; then everything fell into place.

Perhaps we are in a similar situation, waiting for a Newton or an Einstein to come up with a more complete picture of the universe. Meanwhile, we reap enormous benefits from what quantum science has already given us. In that regard, Mermin's suggestion that we get on with the calculations, and leave the philosophical for later, makes sense: it's good to have computers today, even if knowing the ultimate nature of reality has to wait until tomorrow. Or decades from now.

But Hardy, for one, is confident. "Things are only difficult until you figure out how to do them," he says. "Then they become easy."

Dan Falk (@danfalk) is a science journalist based in Toronto. His books include The Science of Shakespeare *and* In Search of Time. *He was a visiting writer at Perimeter in summer 2018.*

Using game theory to tell if a quantum memory is legit

Quantum computing will rely on having a working quantum memory, but how can you verify if that memory really is quantum? Three physicists propose how resource theory and game theory could do just that.

Say you have a quantum system, which you prepare in a special device after breakfast. You go about your day and, just before lunch, you pop back to check the system again. Sure enough, it's still quantum.

But was it quantum that whole time, or is the device simply making you think it was? Perhaps the original quantum state was mapped and that information stored in a hidden file before the state collapsed. That way, when you came back to check it, the device could whip up a new quantum state to match the original.

To the observer, each looks the same: the device might have a functioning "quantum memory" (that is, it stays quantum the whole time) or it might be a quantum-state replicator that uses a classical memory – a hidden file or something similar – to store the information in between readings (meaning it is not, in fact, quantum).

For the nascent field of quantum computing, this is a significant problem. Quantum states are tremendously fragile and can quickly decohere and lose their unique quantum properties. Being able to create robust quantum systems that can be verified and that can maintain their quantum properties over time is one of the hottest areas in quantum research right now.

A key component to this challenge is "quantum memory," or the ability to preserve fragile qubit states over long periods of time. Quantum communication will depend on not only developing such a memory, but also being able to trust that it is truly quantum.

So far, this problem has largely been explored by specialists in quantum channels.

Now, three specialists in quantum information have put forward a new approach to verify quantum systems. Perimeter postdoctoral researcher Denis Rosset and collaborators Francesco Buscemi (Nagoya University) and Yeong-Cherng Liang (National Cheng Kung University) have introduced the first resource theory of quantum memories, opening new research avenues for classifying quantum channels.

"Right now, when people are giving quantum computing talks, they show diagrams of the quantum circuit, which looks something like the lines on a music sheet," says Rosset, who came to Perimeter from the National Cheng Kung University in Taiwan in January.

"At any one time, only two or three lines are intersecting, or interacting, which means the quantum computer operates on only two qubits or three qubits at a time. The rest is supposed to stay preserved in a memory. This is why this work is important. How good is that underlying quantum memory?"

Current tests that verify quantum memory suffer certain limitations. The most commonly used approach, quantum state tomography, takes snapshots of a system and pieces them together to work out the corresponding quantum processes. In this method, all aspects must be controlled and trusted, including the device you use to prepare the quantum state and the measurement instruments you use to measure it. (A "trusted" device does exactly what its mathematical description specifies).

Other tests assess if a quantum system violates a Bell inequality; the problem is, not all quantum entangled states do. That means there are a handful of genuinely quantum memories that could or would fail to be certified.

The trio's paper, "Resource theory of quantum memories and their faithful verification with minimal assumptions," published in the online journal *Physical Review X*, fills those gaps, and it does so in a way that only requires experimentalists to trust their initial state-preparation device. You no longer have to trust your measurement instrument.

The researchers devised a game focusing on a single person. Whereas most physics papers feature "Alice" and "Bob" in separate labs, they created "Abby," who is aiming to sell a quantum memory. In order to certify the quality of the quantum memory, the player asks Abby to operate the memory at two different points in time.

First – after breakfast, perhaps – the player gives Abby a quantum state and asks her to store it in the memory. Just before lunch, the player asks for it to be verified. To do so, Abby receives a second state, which she has to measure in combination with the first state, which she retrieves from her purported "quantum memory."

The player controls what Abby does as she performs a measurement that checks the "quantumness" of the memory. If Abby tries to cheat – say, by using a classical memory device to store the quantum information, instead of maintaining quantumness throughout – she will actually make her situation worse.

"Whatever the player does with a classical resource, they would never be able to win. Of course, if they had access to a genuine quantum memory, they would win your game," Rosset says.

"You force the player to preserve that first state you gave until you get to the second point in time when the second state is received. Your player must measure these two subsystems to win the game. But if they break entanglement – if it loses quantumness – in the meantime, then they cannot win."

This game is shaped by resource theory, which essentially puts price tags on various types of resources, such as tools and processes. Resources that are easily created and replicated, such as written notes or a phone call, are free. Resources that are more complex, such as a quantum bit, come at a cost.

But what is that cost? One cannot simply buy a quantum RAM stick at the local store. However, we can put a "price tag" on a quantum memory, depending on how valuable it is calculated to be. There is not one single way to compute that price tag, though; it depends on the situation in which the resource is used. (In a 2016 article, University of Oxford professor Bob Coecke, Perimeter Faculty member Robert Spekkens, and Tobias Fritz, then a Perimeter postdoc, showed how to compare various types of resources and organize the corresponding price tags.)

Essentially, the better Abby plays and the better her quantum memory performs, the higher the price she can ask for her device.

The approach also removes a significant impediment to quantum memory verification: you don't have to "trust" or verify the measurement device – indeed, any kind of measurement device will work. This helps solve a problem that plagues quantum measurement which can be thought of as: "What ruler do you use to measure a ruler?"

Experimentalists are already in touch with the theorists to discuss ways to test their proposal. Rosset plans to do data analysis for a team in the UK who approached him when the paper was in pre-print.

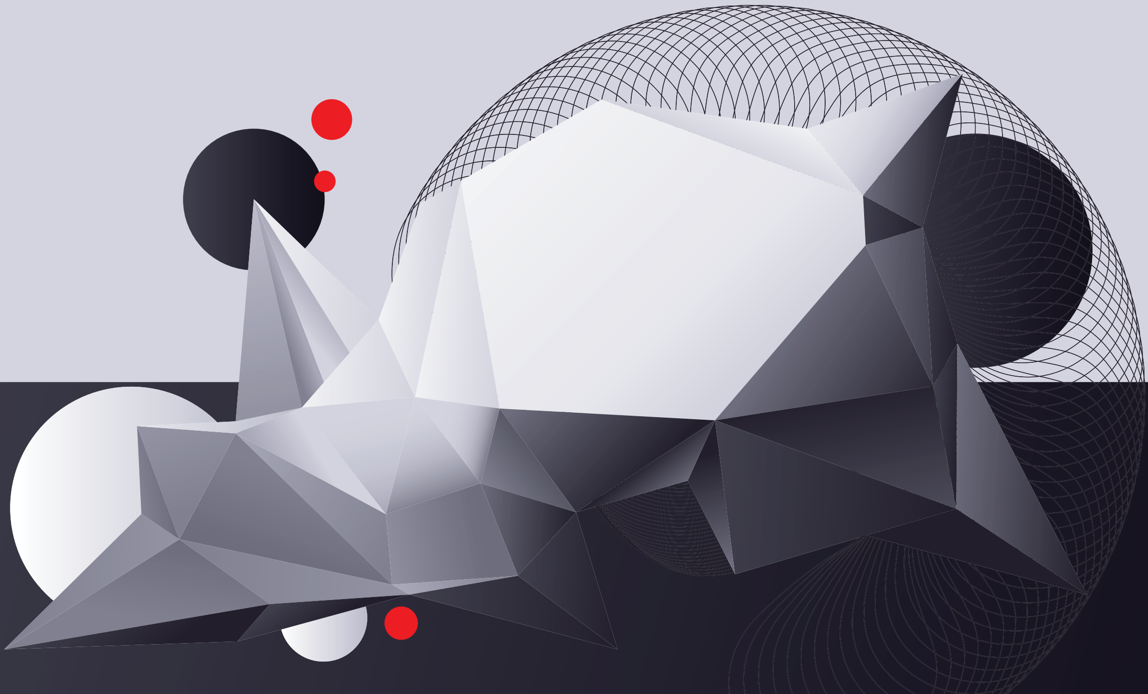
"We'll simulate a quantum memory that has defects, and then we try to see how good these tests are," he says. "We'll make it dirty. It's real-world stuff."

Yet, he expects that the resource theory will turn out to be the bigger contribution to the field. Not only does it help formalize the distinction between quantum and classical memories, it also provides tools to assess and quantify their usefulness.

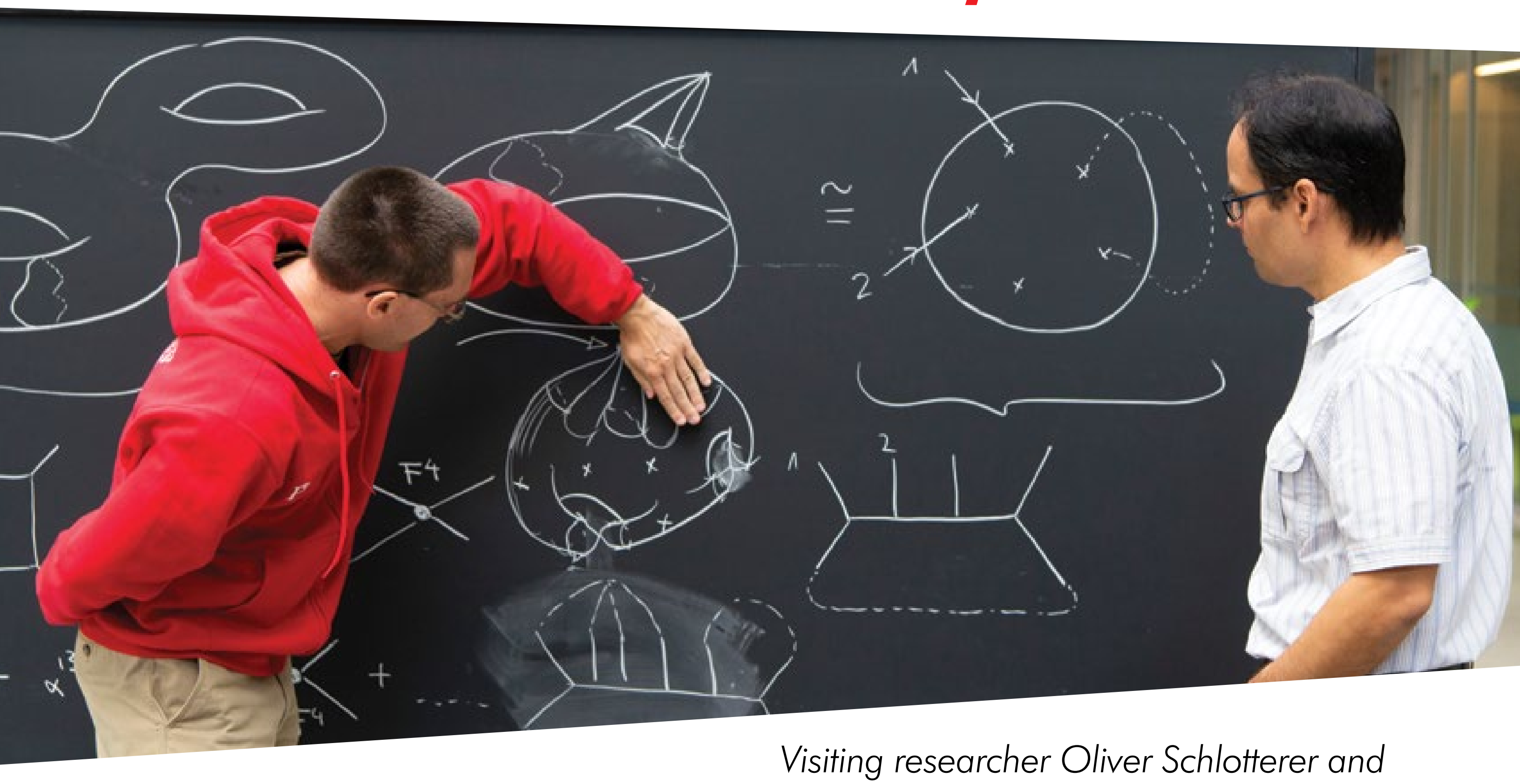
Plus, he points out, it's timely. Coecke, Spekkens, and Fritz's paper essentially codified a language of resource theories so that they can be applied to any system, from information theory to systems engineering.

"Resource theories are a neat way of organizing properties that make quantum systems really quantum," he says. "This paper brings that approach to quantum channels. It fits with the spirit of the times."

– Tenille Bonoguore



The difference a year makes



Visiting researcher Oliver Schlotterer and his host Freddy Cachazo share the benefits of a deep immersion into Perimeter's research and teaching environments.

Cracking the toughest problems in physics is a deeply collaborative endeavour and it's not uncommon for researchers to travel to other institutions to work closely with their colleagues abroad. While most visits last for days or weeks, Perimeter also allows researchers to explore what kind of progress can be made during longer stays. Faculty member Freddy Cachazo and his collaborator Oliver Schlotterer were excited to take advantage of this during a wide-ranging, year-long collaboration beginning in October 2017.

Schlotterer, a postdoctoral fellow at the Max Planck Institute for Gravitational Physics in Potsdam, Germany, and Cachazo, who holds the Gluskin Sheff Freeman Dyson Chair at Perimeter, work on "scattering amplitudes" – mathematical objects that yield theoretical predictions for the subatomic shrapnel that emerges when particles collide – and what they can teach us about fundamental physics. Schlotterer approaches scattering amplitudes from a string theory point of view while Cachazo brings perspectives from quantum field theory.

Inside the Perimeter sat down with them to find out more about the visitor experience.

Inside the Perimeter: Tell us about the experience of visiting for a year. What are the benefits of staying for so long?

Oliver Schlotterer: This one-year format for the visit was completely unique to me. I did go for several two-week visits, four-week visits, to various places before, but I have never had such a relaxed opportunity to really go to a place and get semi-stable and settled.

Freddy Cachazo: One of the major things that you can see is that Oliver has become an intrinsic part of the research group. During this year, he has co-supervised my graduate students. My two students, Alfredo Guevara and Sebastian Mizera, have become very close to Oliver. Both of them have been working on several research projects with Oliver, and at the same time they work on research projects with me – so they have been exposed to a completely different line of research. That's impossible if somebody comes even for a month. A month is not enough to establish a relationship like that.

Here at PI, we have the Perimeter Scholars International (PSI) program. Oliver also became the supervisor of two PSI students, which is impossible if the person only comes for even three months at a time.

Inside: How was your experience teaching in the week-long PSI Winter School?

OS: This winter school is very different. The idea was to get the students actively engaged from the very first day. We would bring a topic or some suggestions of what to work on, but it's really up to the students what happens there.

This format was new to me, so at the beginning I was a bit worried. But it was so fabulous to see the enthusiasm of the students and the fact that they were really willing to dedicate a 10-hour day and longer to really get a grasp on the topic. These were admittedly difficult and technical things that we suggested, but they were willing to dive pretty deep and to get their hands dirty.

FC: I'm not sure that there are many people who would be willing to sit like Oliver did for five days with the students!

OS: You might argue that a school with 200 students sounds like a bigger multiplier factor, but I guess reaching two or three persons deeply is more valuable than giving a shallow exposure to a large amount.

Inside: What's the benefit of immersing yourself in the PI culture instead of doing research the entire time?

OS: Our research interactions were of the form of sharing ideas. It's not at the level that we are doing complete calculations together. It's more like exchanging the visions. I would expect that it might be on larger time scales that the fruits of this will come to appearance.

FC: And the way to share the visions and to establish possible collaborations in the future is to invest in the students. That's one of the reasons we spend a lot of time with students.

Inside: Oliver, you also helped organize a workshop at PI on scattering amplitudes in April. What was the impact of that workshop on the field?

OS: The papers that might have been inspired by the workshop are not yet written, so it's hard to pinpoint anything measurable, but it was great for all of us to have the opportunity to exchange. The participants were very open, also sharing unfinished ideas. This was very valuable diffusion in different directions.

The workshop also coincided with the PSI course that Freddy and I were teaching. The course was three weeks long and the workshop covered the middle one. So we decided to go for an adventurous experiment by outsourcing the middle week of lectures. We invited five of our workshop participants to give lectures. Two of them were given by former PSI students. The students really got a lot of different viewpoints.

Inside: You received a prestigious Starting Grant from the European Research Council, which you will be taking to Uppsala University in 2019. What is the future of your collaborations with Perimeter Institute?

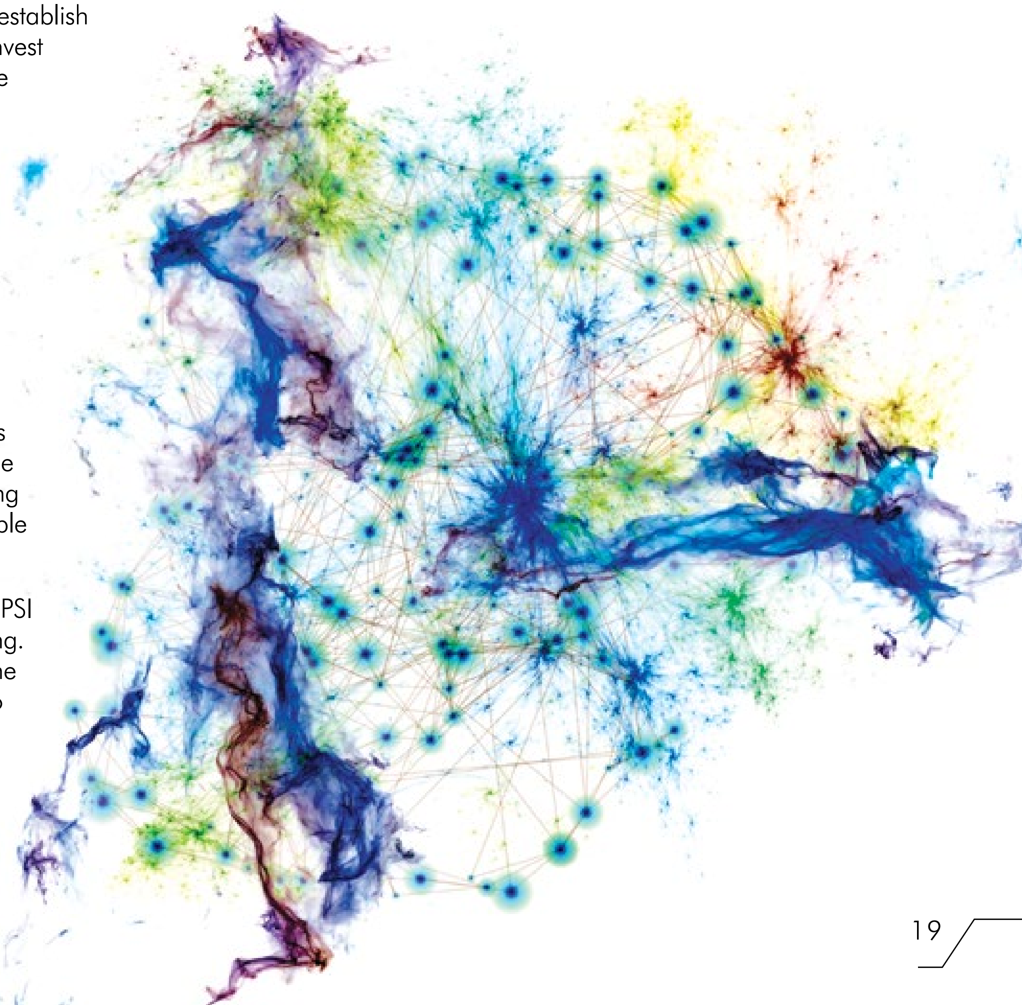
OS: Now I will have the equipment to host Freddy!

FC: Exactly. Part of the benefits of bringing people as visitors is that now we have connections. Now, all of a sudden, we have a very strong bridge with Uppsala University and we didn't really have to go there to establish the bridge. Having somebody like Oliver for a year is doubling the size in terms of impact of what we can do, and in a very cost-effective way.

Inside: What is the most rewarding part of the visitor program?

OS: All this freedom to be spontaneous, to do on a given day what inspired me the moment of waking up. This mixture of interaction on all levels. One of Freddy's students, Sebastian Mizera, has learned a lot of new mathematics that is really inspiring. He already established some collaborations with mathematicians in the US and is doing things that I had no clue of and that I understand will be very valuable for me in the near future.

– Stephanie Keating



PUTTING QUANTUM MECHANICS TO THE TEST

How do you put a theory like quantum mechanics to the test? One way is to develop competing theories and pit them against each other in a cage match.

Quantum mechanics has been a bedrock theory of physics for more than a century, but it does not stand alone. It's part of a vast landscape of theories that could potentially compete with it, including the "boxworld" theory, the "almost-quantum" theory, the Spekkens toy theory, and more.

Defining the full scope of possibilities for such theories has been a fruitful avenue of research since Lucien Hardy published his paper on generalized probabilistic theories in 2001, shortly before joining Perimeter faculty.

Historically, quantum foundations researchers have tried to rule out many of the potential competitors to quantum theory by showing that the theory in question violated principles which are expected to hold in any reasonable physical theory. But there's another approach that works more like a cage match. In this approach, researchers look for places where the different theories predict different results, and then develop experiments to check which predictions were correct. In other words, they narrow down options within the landscape of possible theories using experimental data.

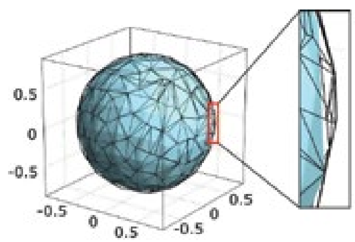
Recently, a team put together by Perimeter Faculty member Robert Spekkens built the cage and staged the match. It's the first time such an experiment – long discussed – has actually been run, and the new results are already shaping up as an important breakthrough in the field.

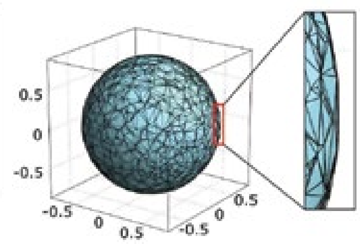
The collaboration consisted of Spekkens and then-Perimeter postdoc Matt Pusey (now at Oxford), together with experimentalists Kevin Resch and Michael Mazurek from the Institute for Quantum Computing at the University of Waterloo. The experiment they designed was deliberately simple. One device prepared a single photon (a particle of light) in a variety of ways. Downstream, another device measured the photon in a variety of ways. Each combination of preparation and measurement was run multiple times, until the data built up to show the frequency at which each outcome of the measurement occurred.

With the data gathered, the team turned its attention to analysis – which proved tricky. They had to find a way of analyzing the data without assuming that quantum mechanics was the correct theory – for how can one test whether or not quantum mechanics is true if the data analysis implicitly assumes that it is?

The issues raised are subtle and the quantitative analysis was quite demanding. But the results are beautiful.

The researchers used some mathematical tools to turn their table of measured probabilities into an easy-to-visualize shape – something even the layperson's eye can evaluate. To zero in on just one set of predictions and results: quantum mechanics predicts that the shape described by the collection of all states should be a sphere. The competing boxworld theory predicts that it should be a cube. The shapes returned by the experiment, however, look like this:





In the left figure, the blue soccer-ball-like shape describes all the ways of mixing together the 100 states prepared in the first experimental run. The blue shape in the right figure describes the same thing for a second experimental run where 1000 states were prepared.

In each case, the slightly larger wire frame shape surrounding the blue shape describes the collection of states that are logically possible given the data. A theory that describes the world would have to fit between the "ball" and the "frame."

It clearly shows that this experiment rules in the sphere predicted by quantum mechanics, and rules out the cube predicted by the boxworld theory. Because small deviations from a sphere also fit, there is room left for some less radical competitors to quantum theory. Or to say it technically, this result puts experimental bounds on how much the correct theory might deviate from quantum mechanics.

In physics, unlike real cage matches, there is no such thing as an undisputed champion, and there are important caveats here regarding whether the states and measurements performed in the experiment were "tomographically complete." But for the moment, quantum mechanics has emerged from its first-ever cage match very much on top.

– Erin Bow

Read the paper at www.arxiv.org/abs/1710.05948

PROJECTIONS

Mapping the interior

"Niayesh Afshordi, 'Cosmological non-Constant Problem'"

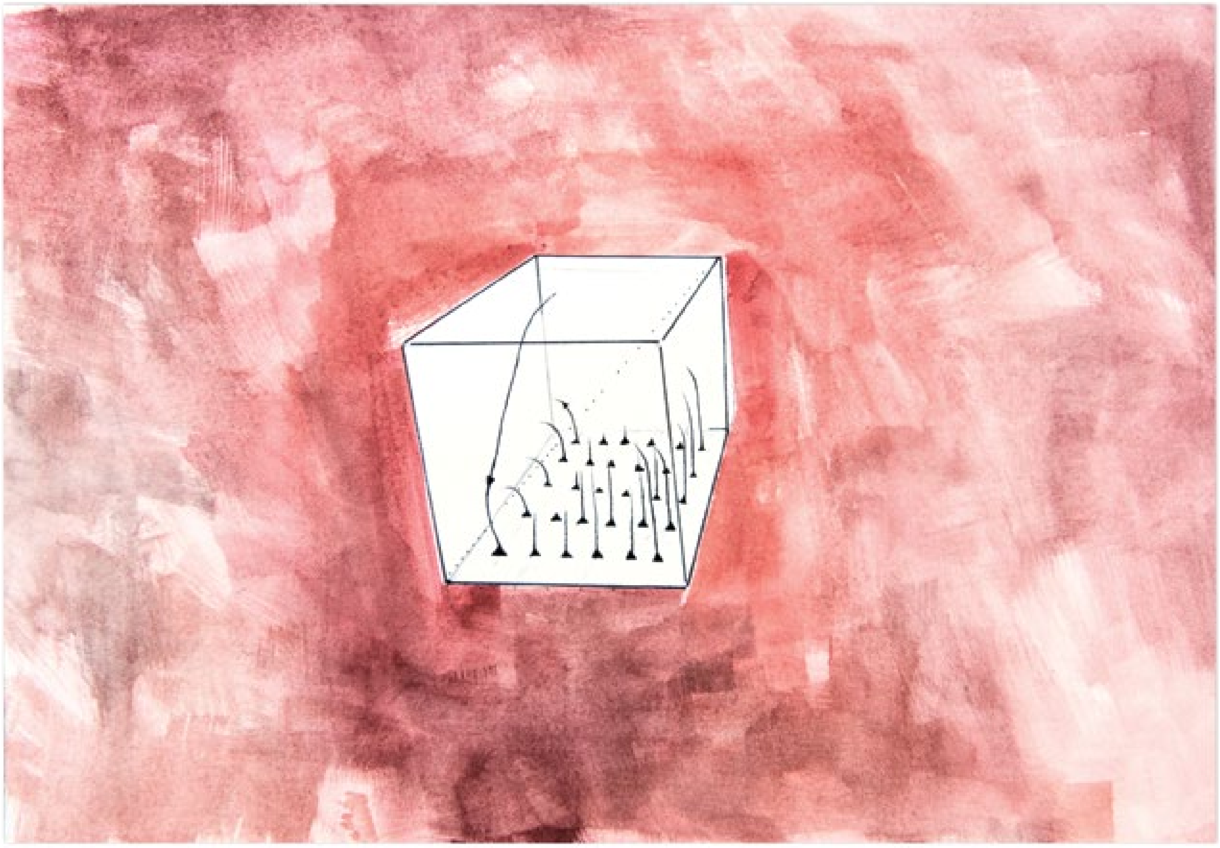
Kaća Bradonjić is a physicist with a research interest in general relativity. She's also a painter with an interest in constructing a visual vocabulary to represent interior landscapes. At the intersection of Bradonjić's two identities – physicist and artist – is the project called Projections.

A few years ago, Bradonjić began painting during talks at scientific conferences she attended, using watercolours to capture her impressions. Her work caught attention and she was invited to come to paint the conference "Asymptotic Safety in the Dark Universe," held in June at Perimeter Institute.

Each painting was begun as the talk began and finished as the talk finished. Each takes the talk's title as its title. Some contain symbols which map onto the ideas of the talk: Feynman diagrams, intersecting planes, asymptotic peaks. Others capture the feel of the room: confidence or uncertainty, conflict or concurrence, the darts of ideas being tossed back and forth.

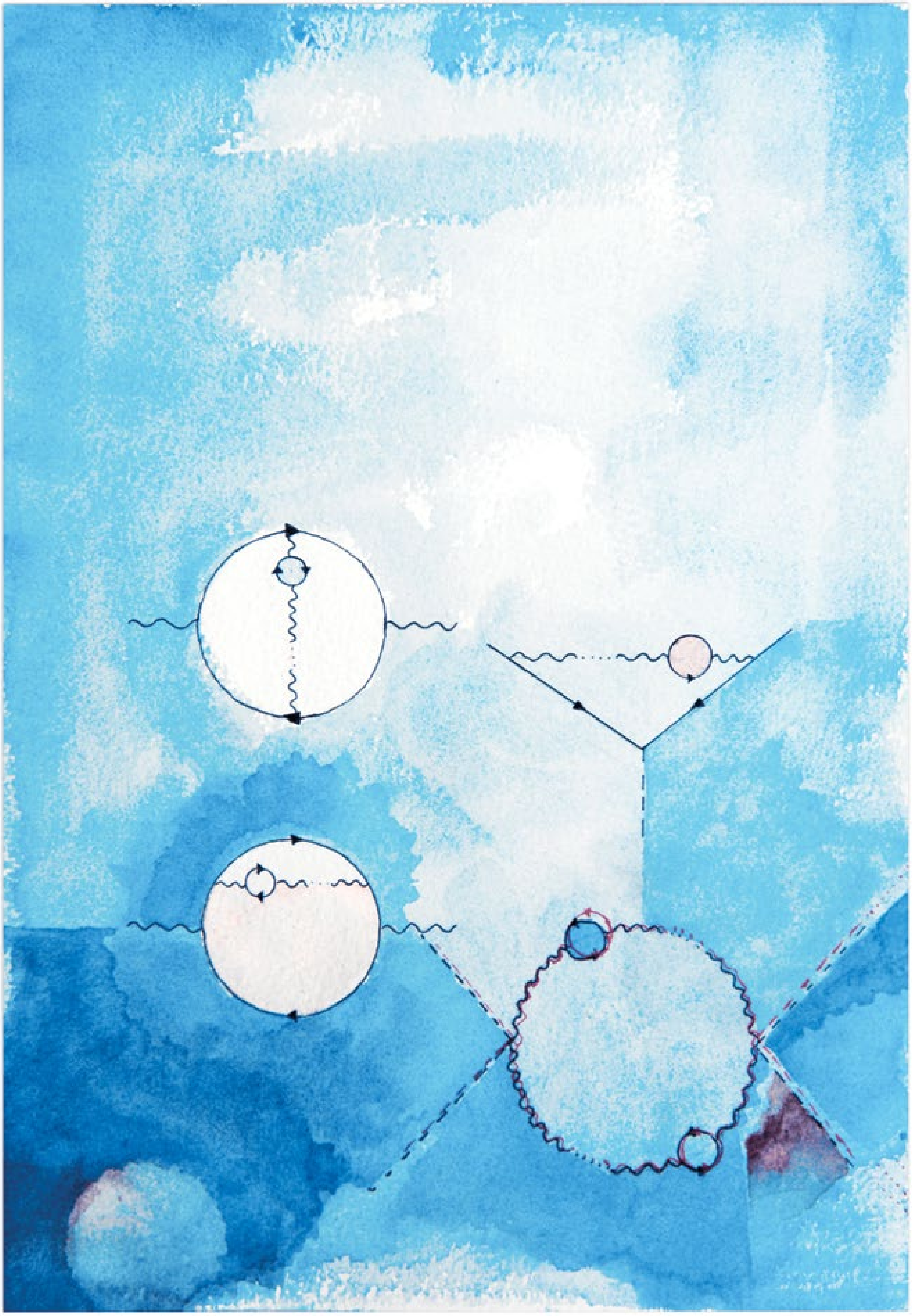
Her hope is to put on public display what's normally a mostly closed-door affair: the emotional energy and complexity of scientific collaboration.

“Nicola Dondi, ‘Constraining Asymptotic
Safety using central charges’”



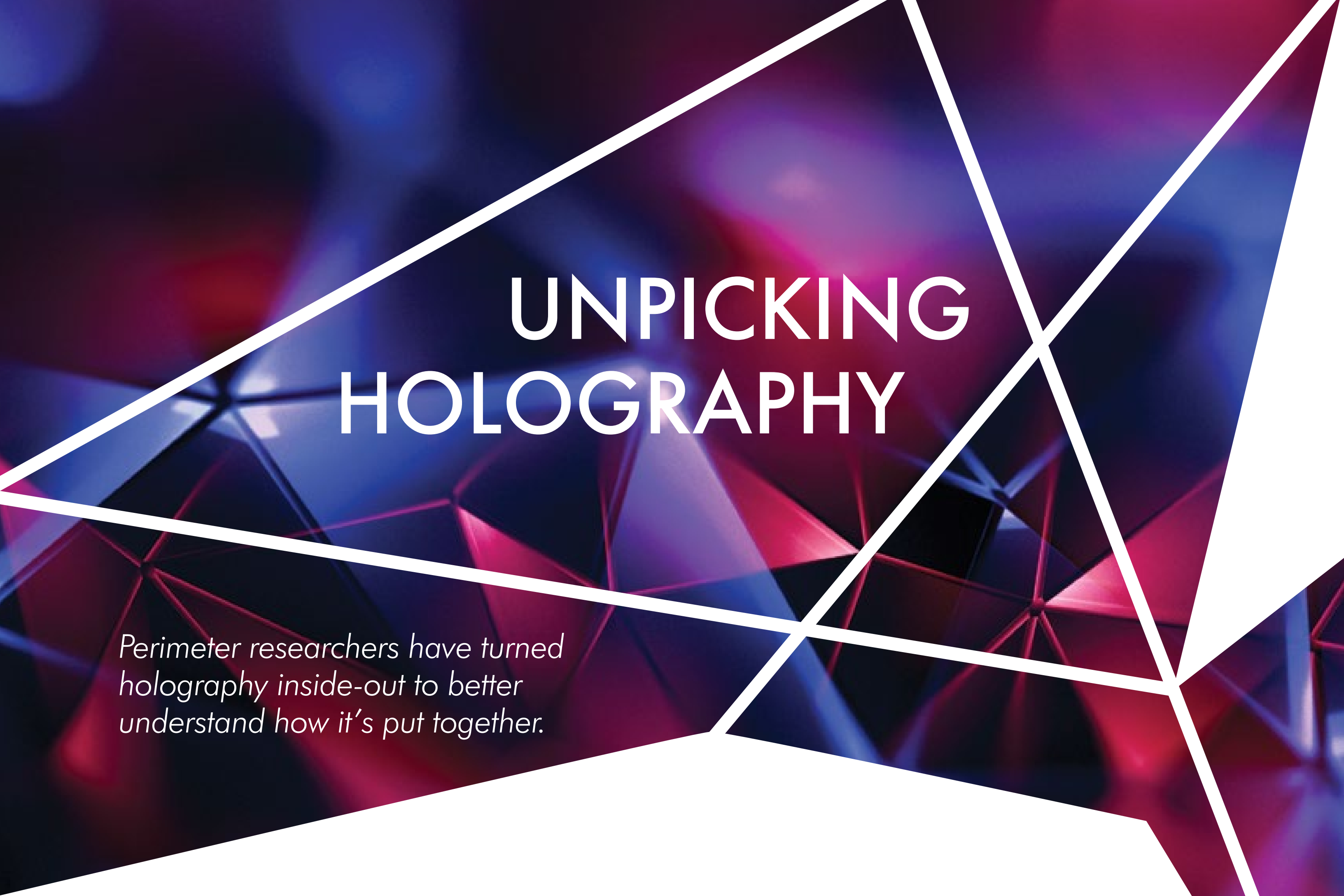
“Steven Abel, ‘Progress in constructing an Asymptotically safe Standard Model, 1’”

“ASIDU, Group Discussion 2”



“Anders Eller Thomsen,
‘Beta functions at large N_f’”

“Astrid Eichhorn, ‘Shedding light on dark matter in asymptotic safety’”



UNPICKING HOLOGRAPHY

Perimeter researchers have turned holography inside-out to better understand how it's put together.

Since it was first proposed in 1997, holography has emerged as an extremely powerful scientific tool that enables researchers to transpose complex theories from one area of physics into something more manageable in another.

But while scientific practice shows that this works, *why* it does so remains something of a mystery. Researchers at Perimeter recently inched closer to an answer to that deeper question by studying a specific question about gravity.

When physicists talk excitedly about holography, they don't mean ghostly projections of deceased singers or the little dove on your Visa card. In physics, holography is a tool or a bridge linking a pair of theories that appear to be completely unrelated. Physicists can use that bridge to transfer problems from one realm of physics to another.

Most often, the two theories linked together by the holographic bridge are a theory of gravity and a quantum field theory. Thanks to holography, a gravitational theory in four-dimensional space (and its fiendishly complex mathematics) can be translated into a more tractable three-dimensional quantum field theory that is, in essence, sketched out on the surface of that space. As with a hologram, one dimension gets subtracted without losing any information.

Usually, holography applies to a special kind of spacetime known as anti-deSitter space (or AdS), and the surface on which the holograph is printed (or, more accurately, the surface that contains the quantum field theory) is infinitely far away.

That's a bit of a challenge, though, as one usually wants to know about how gravity is behaving up close.

In 2016, Perimeter Faculty member Bianca Dittrich and Valentine Bonzom, then a postdoc, showed that holography could also be used in more generic, three-dimensional spacetimes with finite – aka "closer up" – boundaries.

Now, Dittrich and a new team have extended that research. She and postdoctoral researcher Aldo Riello, visiting fellow Etera Livine, and PhD student Christophe Goeller worked together to investigate just what kinds of finite boundaries might work and what the hologram printed on those boundaries might look like.

They worked with an established theory of quantum gravity in three dimensions – two dimensions of space and one dimension of time – and then selected different finite boundaries. (The hologram for such a theory would be a 2D statistical model, printed on a 2D surface such as a hollow sphere or a hollow donut-shaped torus.)

To their surprise, the team found a whole class of different (or at least different-looking) 2D statistical models, depending on the surface chosen. It's the first study to find many different 2D dual models for a single 3D theory of gravity.

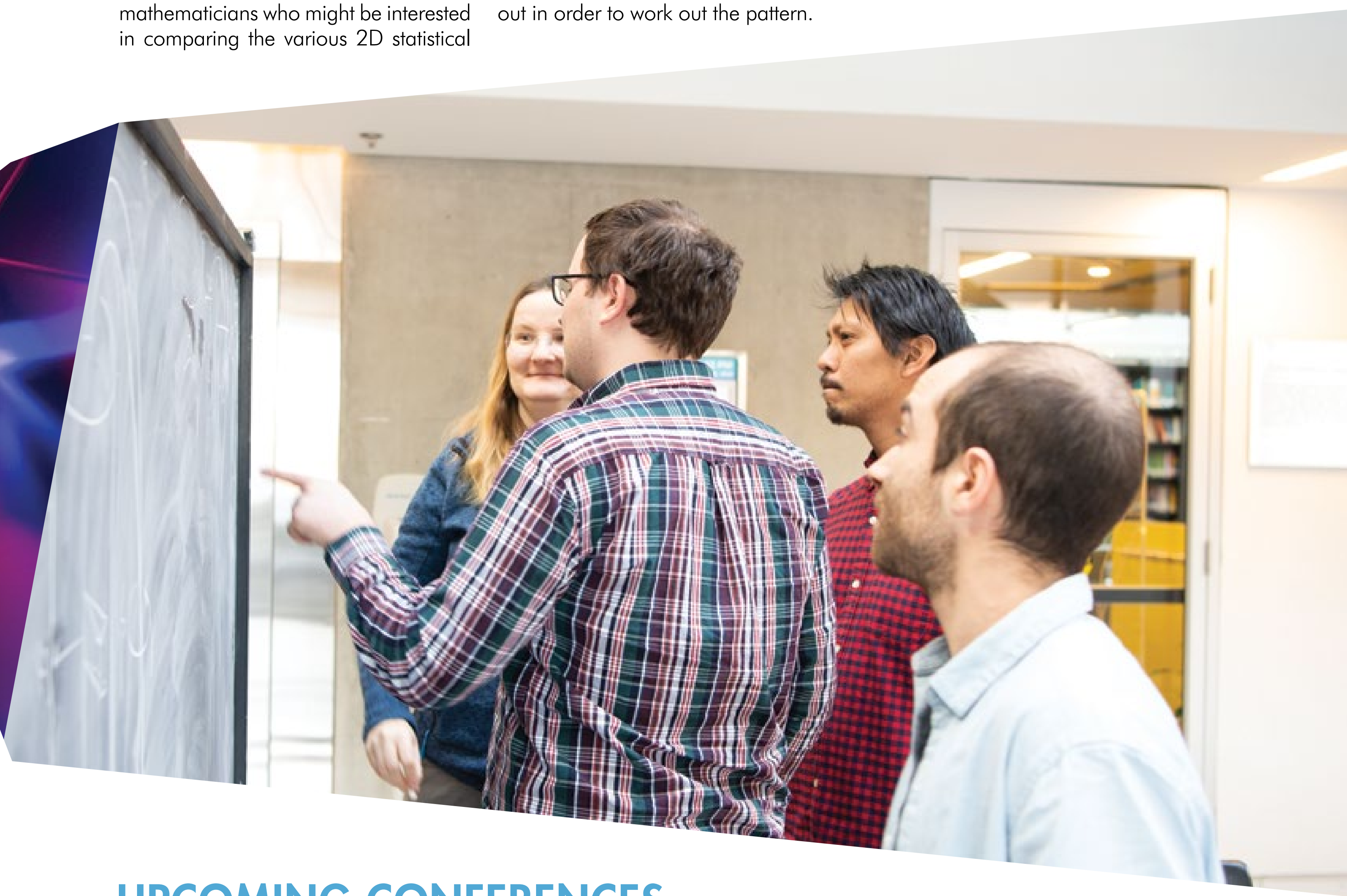
The research gave a fresh look to the established 3D gravity theory and opened a new path of research for mathematicians who might be interested in comparing the various 2D statistical models, looking for equivalences. In the future, the team wants to learn more about the relationship between their choice of boundary wavefunctions and the 2D statistical models generated.

But the real payoff was that, by learning to embed different 2D quantum surfaces in 3D space, the team learned about holography itself. It's a bit like teaching yourself sewing by turning a shirt inside-out in order to work out the pattern.

The team's ultimate and elusive goal is to stitch up a quantum gravity theory fit for our 4D universe. Since holography is powerful, learning more about how holography works at a more fundamental level may well prove powerful too.

– Erin Bow

Read the paper at arxiv.org/abs/1803.02759



UPCOMING CONFERENCES

Perimeter Institute knows that a lively program of conferences and workshops is essential to maintaining a dynamic scientific atmosphere. Don't miss your chance to register for these upcoming conferences:

Cohomological Hall Algebras in Mathematics and Physics
February 25-March 1, 2019

Quantum Matter: Emergence and Entanglement 3
April 22-26, 2019

Quantum Field Theory for Mathematicians
June 17-28, 2019

Bootstrap 2019
July 15-August 2, 2019

Boundaries and Defects in Quantum Field Theory
August 6-9, 2019

Conferences are continually being added. Check www.perimeterinstitute.ca/conferences *for the latest.*

People of PI:

Claudia de Rham, unstuck by gravity

Since her postdoc days at Perimeter, visiting researcher Claudia de Rham has explored gravity from all possible angles.

Claudia de Rham has a peculiar relationship with gravity. She studies it. She is fascinated by it. And she spends much of her free time trying to defy it.

When she's not brainstorming with colleagues at a blackboard or at a computer puzzling over some complex aspect of gravity, she is often escaping its pull in the cockpit of a rented airplane or exploring coral reefs with a scuba tank on her back, suspended weightlessly in seawater.

"It's all part of exploring," says de Rham, whose scientific explorations regularly carry her to Perimeter Institute for research visits. "To fly or to scuba dive, you see yourself in a completely different orientation. It changes your perspective because you can defy gravity in some sense."

A faculty member at Imperial College London, de Rham grapples with deep questions at the intersections of particle physics, gravity, and cosmology, ultimately "trying to understand what the universe is made of, to get closer and closer to a more fundamental description of nature."

That's an ambitious goal – sleuthing out a solution to how the universe really works – but the audacity of the venture is a big part of its allure, she says. "If there's something we don't understand, or some discrepancy in the data, that's a sign – a sign that there is something more for us to learn," she says. "It's a sign that we're on the edge of discovering something new."

She has already made important discoveries, particularly in the field of massive gravity, of which she is a pioneer. She led research that showed the particle carrying gravitational force, the graviton, could be massive, which has major implications for the so-called "cosmological constant problem" regarding the accelerated expansion of the universe.

Her research has earned her a bevy of prestigious awards – including this year the Adams Prize and the Blavatnik Award for Young Scientists – but while she appreciates the recognition, she's more interested in questions than kudos.

Where dreams are born

She traces that insatiable curiosity about the universe to the years her Swiss family lived in Madagascar, where she lay on her back countless nights, gazing at the stars overhead. The view was so majestic, so undimmed by haze or light pollution, that the denseness of the Milky Way looked like strips of gauze stretched across the sky. "It was part of my everyday life to see the stars," she says. "When you look up, look at the deep, deep sky, it makes you dream big."

Her dreams and ambitions carried her through physics studies in France, Switzerland, the UK, and eventually Canada, where she accepted a postdoctoral position at Perimeter Institute in 2006. It was during her time at Perimeter that she nurtured her passion for flying, earning her pilot's license at the local airport and taking to the skies.

On many occasions, when a particular problem in gravity seemed too tough to crack, she changed her perspective by renting an airplane at the Waterloo Region airport. Sometimes she'd fly directly over Perimeter Institute, as if to nudge her subconscious mind into seeking different pathways to the problems she had wrestled with far below.

"I would have all these ideas in my mind, all these problems, but when you fly you have to focus on something very different," she says. "It clears your mind, and all these new connections get created, and you come up with new ideas."

De Rham has returned to Perimeter Institute regularly since she left in 2009, to flesh out new ideas in collaboration with peers, freed from the typical administrative responsibilities of her home institution. She is currently examining the behaviour of gravity coming from pairs of neutron stars spiralling around one another toward an eventual cataclysmic collision. It is research made possible by the landmark 2015 detection of gravitational waves, which de Rham describes as "the most important detection" of her lifetime.

Supporting women in physics

In 2013, de Rham was among the inaugural group of Perimeter's Emmy Noether Visiting Fellows, a program that supports women physicists at critical stages of their careers (see sidebar). For de Rham, then a new mother of one, the Fellowship offered more than just financial support; it provided new collaboration opportunities and much-appreciated help, such as sorting out daycare logistics so she could focus on vexing questions about gravity and general relativity.

The namesake of the fellowships, Emmy Noether, should be "a role model for women and men in physics," says de Rham, who has since had two more children. "It's important that there is not just one picture of what a successful physicist looks like," says de Rham. "Kids see a picture of Einstein and think that's what a physicist looks like, but that's not the full picture at all. There are so many different ways one can contribute to science."

Success to de Rham means finding fulfillment in the journey, whether it's a theoretical journey into the mathematics of gravity, a jaunt above the clouds, or a swim beneath the ocean's surface.

"It is an amazing time to be a cosmologist right now," she says. "It feels like we're really on the forefront of big things. It's very, very motivating."

– Colin Hunter

THE SIMONS

EMMY NOETHER FELLOWSHIPS

The Simons Emmy Noether Fellows Program at Perimeter Institute offers women researchers the opportunity to expand their research, forge new collaborations, and immerse themselves in Perimeter's vibrant research environment. Held for up to a year, each visiting fellowship is tailored to the participant. Supports may include housing assistance, teaching buy-outs, childcare, and more.

Applications are open now, and close January 15, 2019.

Find out more at **perimeterinstitute.ca/research/emmy-noether-initiatives**

The Simons Emmy Noether Fellows Program is generously supported by The Simons Foundation.

A group of 40 high school students from across the world explore the curiosities and possibilities of theoretical physics at Perimeter's International Summer School for Young Physicists.

Figuring out physics with NEWFOUND FRIENDS

Attending Perimeter's International Summer School for Young Physicists (ISSYP) is a once-in-a-lifetime experience for most of the 40 students who attend each year.

For Anwyn Woodyatt, who attended in 2017, ISSYP turned into a twice-in-a-lifetime experience. She enjoyed her time so much that she returned this year as a chaperone. "I wanted to make their experiences as good as mine," says Woodyatt. "We're all still in contact almost every day," she says of her cohort. "It's a big family."

That experience seems universal among ISSYP attendees. The campers take a deep dive into modern theoretical physics, exploring topics such as quantum mechanics and special relativity, while also gaining firsthand exposure to areas of current research.

"I really enjoy being around people who share the same interest, because at school, most of the time you have people who want to drop physics as soon as they can," notes Siena Castellon, a 15-year-old student who recently finished lower sixth form (the equivalent of Grade 12) in the United Kingdom. "Here, it's just amazing to be around people who are accepting of your passion for physics."

Castellon knows a thing or two about the importance of a supportive and welcoming environment. At age 13, she created Quantum Leap Mentoring, a website aimed at children with autism spectrum disorder and other learning differences. Castellon herself has Asperger's syndrome, which she says has augmented her pursuit of physics.

"With Asperger's, you can have special interests – little divisions that you're really fascinated by. For me, that's physics and math. It's really helped me to have this interest." The scientific community on a whole can benefit from being open to neurodiversity, she says. "If we can really harness that talent, we can really improve the community."

Castellon and her fellow ISSYP participants, evenly split between male and female students, came from a broad range of backgrounds, but excitement for physics was the thread that tied them together. Half of the chosen students were Canadian; the others hailed from 16 other countries, including Argentina, India, Italy, Turkey, New Zealand, and the US.

Throughout the two-week program, social activities and field trips (including a visit to SNOLAB, a physics laboratory located two kilometres underground within an active mine in Sudbury, Ontario) are woven between lectures on core physics topics, keynotes from eminent physicists, and small-group mentoring sessions with researchers.

Among the keynote lectures was a talk from Perimeter Institute Director Neil Turok. "The universe is astonishingly simple on large scales, but also deeply puzzling," Turok told the students. "We don't quite understand the reasons for that simplicity."

At the "Life as a Physicist Meet and Greet," students met in small groups with faculty, postdoctoral fellows, and graduate students, where they had a chance to ask what life is like as a researcher. Questions ranged from the logistical ("How do you choose a school?") to the more philosophical ("How can you develop the ability to find the interesting problems within physics?").

For that latter question, Perimeter postdoctoral researcher Ravi Kunjwal had simple advice: "Read as widely as possible. Be voracious in your reading, and the questions will come later. Your brain needs enough raw material to begin ruminating."

During the second half of the program, students were given a taste of the research process by tackling a contemporary physics problem in small-group sessions led by Perimeter graduate students and postdocs. They presented their findings at a poster session, similar to those seen at scientific conferences, on the final day of the program.

"My favourite experience was the mentoring programs because we're working with people who are actual researchers. They're people at the forefront of their field. It's a unique experience," says 17-year-old Aydan Jiwani from Mississauga.

For Marin Schultz, a 17-year-old inventor from Lethbridge, Alberta, the theoretical bent to ISSYP was a welcome complement to the tinkering that he's been doing since he was old enough to play with Lego.

In the third grade, Schultz compared the behaviour of robotic nano-roaches with real-life hissing cockroaches for a science fair project, which ignited a passion for robotics and experimentation. At age 12, he hacked a "mind reading" toy and connected it to a primitive robotic hand, programming it such that the more you concentrated, the more the hand would close. Since then, Schultz has continued to make improvements on his designs, turning his room into a robotics lab.

"Obviously, we're learning a lot of really cool physics," he says of ISSYP. "But on top of that, these sessions have taught me new ways of thinking critically about ideas, and how to pursue the creation of a model for an idea that you get."

Swedish student Gabby Habtezion, 19, says ISSYP has opened her up to the possibility of studying theoretical physics.

"It wasn't really an option before because I was scared of what that would look like," she says.

"With theoretical physics, you gain this whole skill set, so you don't have to just be working in physics or academia. You can work in management, you can work in a lot of different areas. It's more than just learning physical concepts. It's also a way of thinking."

– Stephanie Keating

The 2017/18 edition of ISSYP was made possible by the continued generous support of RBC Foundation, ISSYP's Presenting Partner. Additional support was provided by Maplesoft, as a Perimeter Institute Educational Outreach Champion.

Calling all high school physics aficionados! Applications for the 2019 edition of ISSYP open in December, and close March 31.

www.issyp.ca

THANKS TO OUR SUPPORTERS

An ever-growing group of both public and private donors has helped make Perimeter what it is today: a world-leading centre for fundamental research, scientific training, and educational outreach. We are deeply grateful to all our supporters.

ENDOWMENT FUND

FOUNDER ($150M+)

Mike Lazaridis

$25M+

Doug Fregin

$10M+

Jim Balsillie

GOVERNMENT PARTNERS

Government of Canada

Government of Ontario

ENDOWED INITIATIVES

BMO Financial Group Isaac Newton Chair in Theoretical Physics ($4 million)

Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics ($4 million)

The Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent ($1 million)

PERIMETER RESEARCH MAJOR GIFTS

Centre for the Universe at Perimeter Institute ($5 million)*

Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics ($4 million)

Gluskin Sheff Freeman Dyson Chair in Theoretical Physics ($2 million)

John Templeton Foundation – Templeton Frontiers Program at Perimeter Institute ($2 million)

Krembil Galileo Galilei Chair in Theoretical Physics ($2 million)

Krembil William Rowan Hamilton Chair in Theoretical Physics ($2 million)

Clay Riddell Paul Dirac Chair in Theoretical Physics ($1 million)

Daniel Family P. James E. Peebles Chair in Theoretical Physics ($1 million)

Delaney Family John Archibald Wheeler Chair in Theoretical Physics ($500,000)

Cenovus Energy James Clerk Maxwell Chair (Visiting) in Theoretical Physics

*Anonymous Donor

CORPORATE AND SPONSORSHIP PARTNERS ($100,000+)

Cenovus Energy, in support of the Distinguished Visiting Research Chair program at Perimeter Institute

Maplesoft, Perimeter Educational Outreach Champion

Power Corporation of Canada, proud supporter of EinsteinPlus and Perimeter's Teacher Network

RBC Financial Group, Presenting Partner, International Summer School for Young Physicists

Mike Serbinis and Laura Adams in support of the Theoretical Physics Summer Undergraduate Program at Perimeter Institute

AWARDS ($35,000+)

The Savvas Chamberlain Family Foundation Anaximandros Fellowship

The Joanne Cuthbertson and Charlie Fischer Graduate Student Award

The Hellenic Heritage Foundation Anaximandros Fellowship

Brad and Kathy Marsland Honorary PSI Scholarship Award

Margaret and Larry Marsland Honorary PSI Scholarship Award

ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation

Corinne Squire and Neil Turok

Mac Van Wielingen, Viewpoint Foundation

DIRECTORS CIRCLE ($10,000 TO $49,999)

$25,000+

Bosch Community Fund, on behalf of ESCRYPT in Canada

Donald and Eleanor Seaman Family Foundation

$10,000+

The Boardwalk

Harbir and Monica Chhina

Fondation Famille Vachon

Kitchener Waterloo Community Foundation

- The Musagetes Fund
- The John A. Pollock Family Fund

Robin and Robert Ogilvie

Ildiko and Peter Paulson

Robert and Pearl Radnitz**

Reid Family

The TRH Foundation

Alex White

FRIENDS (UP TO $9,999)

$5,000+

Jerome Bolce

Mary and Ted Brough

Compugen Inc.

J. DesBrisay and M. Cannell

Michael Duschenes

Dorian Hausman

Stephen Lister and Dr. Molly Rundle

Renée Schingh and Robert Myers

$2,500+

Don Campbell

Michael Horgan

John Matlock

$1,000+

Debbie and Ian Adare

Dan and Robin Benson

Rex Breunsbach

The Carson Family Foundation

David Cook

Ben and Mona Davies

Greg Dick

Edward Goldenberg

Stephanie, Robert and Aaron Hilson

Ed Kernaghan

Frederick Knittel

Robert Korthals and Janet Charlton

Carol A. Lee

ODC Tooling & Molds in memory of Leejay Julius Levene

Stefan and Shani Pregelj

W. Michael Roche

Schnurr Family Foundation

Lewis Warburg Foundation**

Jiecheng Zhang

$250 to $999

Chelsea and Keegan Arnott

John Attwell

Mike Birch

Matt Douglas

Chris and Chryssa Geddes

Jane G. Hill

Colin Hunter

Kate Inglis

Sheri and David Keffer

Robert G. Lake

Catherine Little

Mario C. Lourenco

George Meierhofer**

L. Elizabeth Quinn

Neil Steven Rieck

Nancy Ruddell

Catalin Sandu

Rosalind Tracey

Kim Tremblay

Jacqueline Watty

Natasha Waxman

Gerry Wisnoski

… plus 6 anonymous Friends donors

GIFTS OF CELEBRATION, HONOUR, AND MEMORY

Carolyn Crowe Ibele, in memory of Dr. Richard A. Crowe

Simon Haysom, in memory of Elsie Haysom

IN-KIND GIFTS

Steinway Piano Gallery

** Supporter of Friends of Perimeter Institute Inc., a 501(c)(3) public charity in the United States dedicated to promoting and supporting education, research, and programs that expand the public knowledge and understanding of theoretical physics.

This list reflects gifts received between August 1, 2017 and October 31, 2018, and multi-year commitments of $50,000 and more.

Charitable registration number: 88981 4323 RR0001

EMMY NOETHER CIRCLE

Emmy Noether was a brilliant scientist whose work underpins much of modern physics. Perimeter's Emmy Noether Initiatives – funded by Emmy Noether Circle donors – support and encourage women in science.

FOUNDING DONOR

The Bluma Appel Community Trust

MAJOR GIFTS

The Simons Emmy Noether Fellows Program at Perimeter Institute ($600,000)

$100,000+

Anne-Marie Canning

Dr. Scott and Sherry Vanstone and family

$25,000+

BMO For Women

Linamar Corporation

Patrice E. Merrin

$10,000+

Burgundy Asset Management Ltd.

$5,000+

Andrew and Lillian Bass

Mark Caplan and Claire Angus

Jennifer Scully-Lerner**

$2,500+

Maria Antonakos and Harald Stover

Heather and John Clark

$1,000+

Andrea Grimm

Beth S. Horowitz

Lisa Lyons Johnston

Vicki Saunders

David Tovell

$250 to $999

John Attwell

Jeremy Bell and Sunny Tsang

Marsha Eberhardt

Nicholas Reaburn

Betty Robinson

Sonya Walton

TEACHERS BECOME PUPILS AT IMMERSIVE PHYSICS CAMP

Forty-four teachers from around the world gathered for EinsteinPlus at Perimeter Institute, sharing ways to bring physics to life in their classrooms.

The purpose of education, Albert Einstein once wrote, "is not the learning of many facts but the training of the mind to think."

Such training requires a high tolerance for being stumped, especially when it comes to mind-bending topics like quantum mechanics, general relativity, and the mysteries of black holes.

Stumped was a recurring state of mind among 44 teachers from around the world who assembled at Perimeter Institute for EinsteinPlus, a week-long summer program that, true to its namesake, encourages mental calisthenics over rote memorization.

The underlying idea is that if the teachers can solve a vexing physics problem through teamwork and tenacity – and have fun in the process – they can inspire the same problem-solving perseverance in their students.

Over the course of the week, the teachers – who came from Estonia, China, the US, Portugal, the Netherlands, and across Canada – trained their minds by using their hands in a series of classroom-ready demonstrations and experiments. They used beach balls to understand time dilation, buckets of water to understand force and momentum, and cheap household knickknacks to create "Dollar Store Demos."

In one particular exercise, the teachers were divided into teams of four, each group armed with a laminated map of the Earth, a ruler, a dry-erase marker, and a piece of string. Using only those tools and a bit of mathematical know-how, they were tasked with figuring out how complex, ultra-precise GPS navigation technology works.

"Uh..." says Lucas Feitosa Campos, a teacher from São Paolo, Brazil. "Hmm..."

His puzzlement was shared by many in the room, who were trying to triangulate the position of an imaginary GPS device somewhere on Earth by applying the Pythagorean theorem, the speed of light, and some ingenuity.

Gradually, as groups talked through potential solutions, the air of befuddlement was replaced by the buzz of progress. Eventually, each group teased out a solution to the problem – some correct, some close enough, and some enlighteningly wrong.

Failure is an important part of the scientific process, says Campos, and can be much more instructive than memorizing formulae and facts.

"It's not just the content of the lesson that's important, but the philosophy of learning something by trying to figure it out," he says. "This philosophy of learning-by-doing should be spread."

And that is exactly what he intends to do in his home country: spread the EinsteinPlus philosophy among Brazilian teachers. Campos is an outreach coordinator at the International Centre for Theoretical Physics at the South American Institute for Fundamental Research (ICTP-SAIFR) in São Paulo. When Perimeter Institute forged a partnership with ICTP-SAIFR in 2015, Campos attended a version of EinsteinPlus presented there by Perimeter's Educational Outreach team.

This summer, he travelled to Canada – along with fellow ICTP-SAIFR outreach coordinator Ana Serio – to glean more ideas and techniques for launching the Brazilian version of EinsteinPlus. Together, they'll train Brazilian teachers with similar activities, who in turn will train their fellow teachers, all of whom will take the techniques to their classrooms.

All the EinsteinPlus participants will do the same, sharing what they've learned with their peers back home, in a model that maximizes the number of students reached.

The hands-on, experiential learning of the EinsteinPlus program "allows us to feel reconnected with the magic of teaching," says Serio.

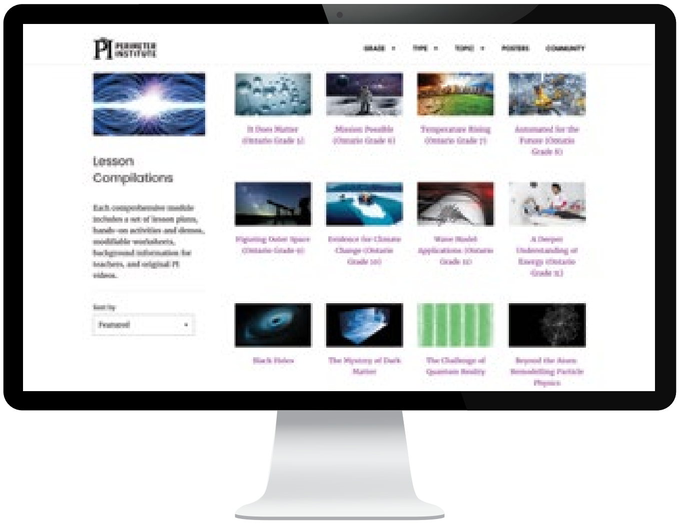
"If we can make more teachers feel like this, and they can share that feeling with their students, it can be contagious and help change education."

– Colin Hunter

EinsteinPlus and Perimeter's Teacher Network are proudly supported by by Maplesoft as a Perimeter Institute Educational Outreach Champion.

Exploring the physics all around us

From climate change to gravitational waves, three new classroom resources give students a deep dive into modern physics.



How does ocean temperature contribute to climate change? If energy can't be destroyed, how does it transform? And how do soundwaves help us see the invisible?

These tangible, real-world questions are coming to life in classrooms thanks to three new educational resources created by Perimeter Institute.

Available in English and French, each free resource explores a different aspect of the universe, using lesson plans, hands-on activities and demonstrations, modifiable worksheets, and videos.

"Because we're working with the researchers, we get the deeper picture," says Dave Fish, a high school physics teacher who is spending a sabbatical with Perimeter's Educational Outreach team.

"We make sure the resources can work in a classroom. They're all tested in classrooms as part of the development program, and we have other teachers review them."

Every resource can be modified to suit students' needs – something Fish particularly appreciates. "As a teacher, you always get these resources that are almost right, but there's a word or a question you don't like. You end up doing a crude cut-and-paste or telling your students to ignore something," he says. "When I use the Perimeter resources in my class, I'm able to tweak it to get it just the way I need it."

This year's three new releases are "Evidence for Climate Change" (aimed at Grade 10), "A Deeper Understanding of Energy," and "Wave Model Applications" (both aimed at Grade 11). They join a suite of resources created thanks to funding from the Ontario Ministry of Education, with another four in development aimed at Grade 12, college, and early-university courses.

Not only are the resources free, but every hands-on lesson can be put into practice using inexpensive items. That low-budget approach is not an accident, says Perimeter Educational Outreach Director Greg Dick.

It's a deliberate effort to level the playing field so that all students have the same access to engaging science. "Our classroom resources are designed to create deep learning opportunities for all students, to let them really experience the science and develop the skills that will propel their future," he says.

– Tenille Bonoguore

For teachers:
Visit www.resources.perimeterinstitute.ca to explore and download all of Perimeter's free in-class teaching resources.

WHERE DID IT COME FROM?

THE OVERLOOKED, SELF-TAUGHT PHYSICIST WHO LAID THE GROUNDWORK FOR LASERS

S.N. Bose was a Bengali mathematician who taught himself German in order to study physics. He then solved a problem that had stumped even Einstein.

You wouldn't be reading this if it weren't for lasers.

Though mostly hidden from sight, lasers are the backbone of our information economy. As the light in fibre optic cables, they make the internet possible. They read and write data onto CDs and DVDs. They guide airplanes and talk to satellites. Even books are not immune: most of them are laser-printed.

The roots of the laser go back to 1917, when Einstein discovered "stimulated emission," where an atom in a high-energy state is brushed by a photon of the right energy, and emits a second photon identical to the first.

It would be decades before the theory of stimulated emission became the technology "light amplification by stimulated emission of radiation" – or "laser" for short. Along the way, there were dozens of scientists and engineers, the dawn of fields like quantum chemistry and solid-state physics, and an epic patent battle that turned on a sketch that a graduate student had had notarized at a candy store in the Bronx.

But back at the beginning, there was a sweet-natured self-effacing physicist named Satyendra Nath Bose – S. N. Bose. Born in Calcutta (now Kolkata), India, in 1894, Bose was a child prodigy who studied mathematics at university, eventually earning a master's degree.

Unlike most world-shaping scientists, he did not go on to earn a PhD. Instead, he began teaching himself physics, borrowing textbooks on the newest theories written in German and then teaching himself German so that he could study them.

Bose dove into physics in about 1917. It was an exciting time for the field. In 1900, German scientist Max Planck had discovered that electromagnetic energy could be emitted or absorbed only in discrete chunks, which he called quanta. It was a moment that changed physics, the dawn of the quantum age.

But there was something unsatisfying about Planck's discovery. Even Planck admitted he had introduced his famous formula as a kind of fudge factor to make the theory fit the data. Many physicists, including Einstein, tried to derive Planck's formula from first principles, but all failed. Bose set himself against the problem cheerfully, seemingly unaware that it had already defeated the best minds of the age. And amazingly, the young scientist solved it.

Bose's key insight was to introduce a brand new kind of statistics. In normal statistics, if you flip two coins, they have four possible ways they can fall: head-head, head-tail, tail-head, and tail-tail. The odds of getting two heads is therefore one in four. Bose suggested that because you can't tell one photon from another, head-tail from tail-head are indistinguishable: effectively one possibility. If coins worked this way, the odds of getting two heads from two coinflips would be one in three.

To both physicists and mathematicians, this sounded ridiculous. To Bose, who was both, the proof was in the pudding: his new statistics worked. He wrote a paper on the matter, "Planck's Law and the Hypothesis of Light Quanta," but the journals he sent it to rejected it. So Bose did another ridiculous thing: he sent the paper to Einstein personally.

The year was 1924. Einstein was famous already and flooded with mail. Still, the paper caught his eye – possibly because it tackled a problem that he had been unable to solve. He translated the paper into German and arranged to have it published by one of the best journals in the field, *Zeitschrift für Physik*, with a note: "This appears to me an important step forward."

Einstein was understating it. Bose's discovery was so important that Einstein began work on a series of papers on what he termed "Bose statistics" – they're called Bose-Einstein statistics now. It was so important that particles that obey such statistics – particles that like to occupy a single quantum state, lying indistinguishably head-tail and tail-head on top of each other – came to be called bosons. Photons, it turns out, are bosons.

Which brings us back to lasers. A typical beam of non-laser light is like a choppy sea – the quantum waveforms from the different photons overlap and crash into each other and partially cancel each other. In a laser beam, all the waves are moving together to produce a single big-wave train – as if all the power of the ocean were concentrated into one wave. This is called coherence, and it's the reason laser light packs such a punch and is so useful in transmitting information.

The coherence is possible because many photons can occupy a single quantum state. Without Bose's remarkable insight and powerful new statistical tools, physicists could never have understood this – let alone have harnessed the phenomenon to create new technologies, and then new industries, and then new economies.

As for Bose himself, he somehow gained the reputation of a genius who didn't do enough with his gift. Perhaps it was because he didn't concentrate solely on physics: he did research in minerology, chemistry, geology, anthropology, zoology, engineering, and literature in both Bengali and English. Perhaps it was because he was soft-spoken. When Marie Curie told him he'd have to learn French to work with her at the Radium Institute, he was too shy to tell her that he already spoke it fluently. When other Indian scientists asked why their homegrown quantum founding father had never won a Nobel Prize, Bose demurred: "I have all the recognition I need," he said.

And maybe so. He was, by all evidence, happiest in front of a chalkboard with a handful of students, or talking with his friends over endless cups of chai. He liked company. When Paul Dirac visited him in India, he complained about picking up some of Bose's students in an already crowded car: "Oh, we believe in Bose statistics here, Paul!" Bose laughed.

Bose died, still happy, in 1974.

In 2012, a new kind of boson – the Higgs boson – was discovered, and the press scrambled to write about Peter Higgs. In India, though, they also wrote about Satyendra Nath Bose. And when they wrote about the boson, they used a capital B.

– Erin Bow

ONE LASER BREAKTHROUGH REALLY DID CHANGE THE WORLD

Canadian Donna Strickland shares the Nobel Prize in Physics for work that unleashed even more power from lasers.

In 1985, it took just three pages for then-PhD student Donna Strickland and her supervisor Gérard Mourou to explain their breakthrough technique to produce high-energy, ultrashort laser pulses.

The paper's abstract was almost as short and sharp as the work itself: "We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented."

Prior efforts to boost lasers had caused equipment to explode. By using a pair of gratings (components in optics that split and diffract light) to stretch a laser beam pulse, Strickland and Mourou were able to amplify the light and then squeeze it back together for a short, powerful blast.

Their work led directly to the development of laser eye surgery and new industrial techniques, as well as more powerful laser tools for scientific research. And this year, the pair shared the Nobel Prize in Physics for the effort.

Strickland is now a Professor at the University of Waterloo, where she is a self-described "laser jock." Her work focuses on ways to create even shorter pulses – approaching a single femtosecond (a quadrillionth of a second) in duration – in order to make "freeze frame" movies of molecular motion.

"At some point it would be nice to have a movie where you could see atoms just vibrate," Strickland told the CBC. "These items are vibrating on the timescale of just a few femtoseconds. So that's why you need a short pulse: if you're going to freeze that action the pulse has to be shorter than that timescale of the motion."

The win makes Strickland only the third woman to win a Nobel Prize in Physics, alongside Marie Curie and Maria Goeppert Mayer. "I'm honoured to be one of those women," Strickland said. "We need to celebrate women physicists because we're out there, and hopefully in time it'll start to move forward at a faster rate."

Strickland and Mourou shared half the 2018 Nobel Prize in Physics. The other half was awarded to Arthur Ashkin for his own novel use of lasers: using them as "optical tweezers" to grab and control microscopic objects like viruses and cells.

– Tenille Bonoguore

New summer program to support exceptional undergrads

Perimeter's undergraduate summer program aims to broaden horizons.

Next summer, 20 of the world's top undergraduate physics students will immerse themselves in Perimeter's dynamic research environment as part of the inaugural Undergraduate Theoretical Physics Summer Program at Perimeter Institute.

Open to students entering their final year of an undergraduate physics degree, the program will introduce participants to exciting problems in the field and the researchers working on them.

Students will spend two weeks during the summer taking in lectures from leading international physicists and experiencing the full breadth of Perimeter's research environment by attending conferences, group meetings, and talks.

"We are thrilled to be able to offer this program, which allows us to bring talented, motivated, and creative undergraduate students from Canada and around the world to Perimeter," says James Forrest, Director of Academic Programs at Perimeter.

"A program like this for undergraduates is something we have wanted to offer for some time, so we are very much looking forward to welcoming our first class in May 2019."

The new program will bridge the gap between Perimeter's International Summer School for Young Physicists, aimed at high school students, and the Perimeter Scholars International graduate-level training.

Mike Serbinis and Laura Adams with Perimeter Institute Board Chair Mike Lazaridis at the announcement of their gift.

In addition to research training, the program will showcase the applicability of physics to other areas of science and the opportunities that physics training offers beyond academia.

To ensure all qualified students are able to attend, the program has no fee for application or attendance; travel to and from the students' home cities will be paid for, as will all meals and accommodation.

Up to 10 students from the program will also be invited to spend the rest of the summer working as research assistants with Perimeter researchers. Those students will then have an opportunity to present their work to the Perimeter community in a poster session similar to those held at scientific conferences.

The program is partly funded by husband and wife Michael Serbinis and Laura Adams. Serbinis, a tech entrepreneur and Perimeter Board member, is the founder and CEO of League. Adams runs Morgan Stanley's Capital Markets business in Canada.

The first undergraduate summer school will run from May 27 to June 7, 2019. Applications are open now, and will close January 7, 2019.

– Stephanie Keating

For more details about the program or the application process, visit www.perimeterinstitute.ca *and look under "Training – Undergraduate students."*

Neil Turok appointed to Order of Canada

When Neil Turok moved to Canada to lead Perimeter Institute in 2008, he brought boundless enthusiasm for the great scientific adventure that lay ahead. But there was one thing Turok could never have predicted: how warmly Canada would welcome him.

In June, Turok was named an Officer of the Order of Canada (Honorary) in recognition of his "substantial contributions as a scientist to the field of theoretical physics and cosmology, providing new models that test fundamental theories of the universe."

Turok sees his appointment as a broader recognition of Perimeter's work, and of all the people whose support is essential to the endeavour. "This never could have happened without the teamwork and support of many people," he said. "We are pursuing a powerful ideal together – to discover new truths about nature, to enable brilliant young scientists to blossom, and to share with everyone the wonder and hope that science brings."

Dirac Medal for distinguished researchers

Three distinguished researchers with strong ties to Perimeter Institute have won the prestigious 2018 Dirac Medal and Prize from the International Centre for Theoretical Physics. Subir Sachdev holds the Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting), while Dam Thanh Son and Xiao-Gang Wen are both Perimeter Distinguished Visiting Research Chairs. They shared the prize "for their independent contributions toward understanding novel phases in strongly interacting many-body systems, introducing original cross-disciplinary techniques."

A weighty honour for a DVRC

The American Physical Society (APS) has awarded the 2018 Einstein Prize to Abhay Ashtekar, a professor at Penn State, a founder of loop quantum gravity, and one of Perimeter's Distinguished Visiting Research Chairs. The prize is the highest honour bestowed by APS in the broad area of gravitational science. Ashtekar was singled out for his "numerous and seminal contributions to general relativity, including the theory of black holes, canonical quantum gravity, and quantum cosmology."

Clay Riddell, 1937-2018

We note with sadness the passing in September of long-time Perimeter friend Clay Riddell. A leading philanthropist from Calgary's oil and gas sector, Clay was a no-nonsense business pioneer with deep dedication to his country and community. In 2015, he established the Clay Riddell Paul Dirac Chair and established a strong rapport with chairholder Pedro Vieira. He also attended many Perimeter events in Calgary and, along with Perimeter Board member Joanne Cuthbertson, co-hosted a memorable evening with Nobel Prize winner Art McDonald. All at Perimeter extend our condolences to Clay's family.

Exploring science under the ground

Nobel winner Art McDonald recently took members of Perimeter's leadership team and some long-term supporters on a tour of the SNOLAB facility deep underneath Sudbury, Ontario, where they saw first-hand the union of theory and experiment.

Teaching teachers, now in French

Perimeter's summer boot camp for physics teachers, EinsteinPlus, was offered in French for the first time this year. Francophone high school teachers from across Canada gathered in Trois-Rivières, Quebec, for a one-week intensive course designed to help them bring modern physics into their classrooms. It was an experiment that bears repeating: Perimeter's team in Quebec is already planning the 2019 edition of the Cercle scientifique EinsteinPlus.

Elizabeth Gould gets the Pearson medal

Elizabeth (Beth) Gould has earned the W.B. Pearson Medal from the University of Waterloo for her PhD thesis, titled "New Views on the Cosmological Big Bang." Gould completed her PhD at Perimeter under the supervision of Perimeter Associate Faculty member Niayesh Afshordi. The W.B. Pearson Medal is presented annually to one PhD student in each department in the Faculty of Science in recognition of creative research as presented in the student's thesis.

Four PhD students win Vanier scholarships

They came to Canada chasing big questions. What they found is a country willing to invest in their potential to find answers. Four PhD students at Perimeter Institute and the University of Waterloo have received prestigious Vanier Canada Graduate Scholarships. Anna Golubeva, Florian Hopfmueller, Fiona McCarthy, and David Schmid will each receive $50,000 a year for three years during their doctoral studies. The Vanier scholarships are designed to help Canadian institutions attract highly talented doctoral students from around the world. Scholars are chosen based on academic excellence, research potential, and leadership qualities. "I came to Canada because I believe Canada is especially supportive of foundational research in physics," said Schmid. "Winning this award feels like a personal validation of that belief."

CCAE awards

Perimeter Institute made a resounding debut at the Canadian Council for the Advancement of Education (CCAE) awards, winning medals for outstanding achievements in communications, publications, and fundraising. The Council's annual Prix d'Excellence awards are the benchmark for achievements in educational advancement in Canada.

Perimeter won gold for best website (insidetheperimeter.ca), best poster (the Forces of Nature series), silver for best fundraising materials ("Giving Tuesday" featuring Sumati Surya), and bronze for best media relations initiative (Innovation150 editorials).

Knighthood for Michele Mosca

Michele Mosca has earned many awards and distinctions for his pioneering work in quantum computing and cybersecurity, but a knighthood was an unexpected first. In July, Mosca was appointed as a Knight in the Order of Merit by the Government of Italy. The knighthood recognizes the contributions Mosca, who is of Italian descent, has made to quantum information science and digital security, as well as teaching and outreach. "I am honoured and humbled to be recognized with this distinction," said Mosca, who was among the first researchers recruited to Perimeter Institute when it was founded in 1999.

Sharing the good news

Perimeter is in good company when it comes to sharing stories of science. InsideThePerimeter.ca was one of two runners-up in the 2018 People's Choice Award for Favourite Canadian Science Site. The winner was The Marine Detective (themarinedetective.com), which explores science from the north-east Pacific Ocean. Co-runner-up was Research2Reality.com, a general science website covering leading-edge Canadian research.

John Brodie Prize winner

Congratulations to condensed matter researcher Markus Hauru, who was awarded the 2017 John Brodie Memorial Prize. The prize is presented annually in honour of John Brodie, one of the first postdoctoral researchers at Perimeter. Hauru began his PhD at Perimeter in 2014 under the supervision of Guifre Vidal and is now a postdoctoral researcher at the University of Ghent.

Luke Santi Award winner

As a child, Aidan Richards would pepper his parents with a barrage of questions about why the world is the way it is. "I had a general sense of just wanting to know everything," said Richards, who is from Mono, Ontario. That curiosity is serving him well. Now a first-year student at Queen's University, Richards has been awarded this year's Luke Santi Memorial Award for Student Achievement. The award is presented annually to a Canadian postsecondary student who embodies the qualities of the late Luke Santi, a high school student and friend of Perimeter who had a passion for research and discovery, earning top marks while volunteering his time in service of others.

Neil Turok delivers OECD keynote

Perimeter Director Neil Turok shared his insights about creativity, curiosity, and entrepreneurialism with the Global Forum on Productivity, held in Ottawa in June. Policy leaders from OECD nations (Organisation for Economic Co-operation and Development) discussed cutting-edge science, new technologies, and fresh approaches in education and training.

How are elements made?

Has anyone told you that you are made of star stuff? It's true.

PI KIDS ARE ASKING

An element is any substance made up entirely of one particular type of atom – the basic building blocks of stuff.

We know that elements have three ingredients: protons, neutrons, and electrons. These are some of the tiniest particles in nature. Each kind of atom, and therefore each element, is defined by how many protons it has in its nucleus.

We can find more than 90 elements on Earth today. The lightest element – hydrogen – has just one proton at its core. Next comes helium (which has two protons), then lithium (three protons), all the way through to uranium, which has 92 protons at its heart.

If you've ever seen a periodic table, though, you'll know that's not the end of it. There are actually 118 elements: the rest were either created by people or are trace elements that are created when other elements decay. The periodic table maps all of the elements out and groups them specific ways. (Fun fact: 2019 is the International Year of the Periodic Table!)

But where do they come from? It's a great question with a dazzling answer. All of the elements around us – the itty-bitty pieces that combine together to make our hair, our clothes, the grass, and trees – got their start as stars.

The lightest elements – hydrogen, helium, and lithium – formed shortly after the big bang, once the universe was cool enough for protons, neutrons, and electrons to combine without being torn apart.

After the universe cooled further and stars formed, the super-hot fusion that powers stars took those first three "big bang" ingredients and turned them into heavier elements.

It all starts with the fusion of hydrogen: atoms of hydrogen are combined to create helium and energy (light). That energy stops the star from shrinking in on itself due to gravity. But once the star runs out of its initial fuel, gravity takes over and the core collapses, leaving a hydrogen-helium shell.

Then the cycle starts again. The condensed core heats up and now has the power for the next stage: the fusion of helium atoms. That produces two more elements – carbon and oxygen – which form new shell layers within the star.

For small stars like our sun, that's the end of the story. They don't get hot enough to fuse heavier elements. But for massive stars, that fuse-collapse-fuse cycle continues, driven by the huge gravity of its own core. Each stage gets hotter and shorter, generating more and more elements – all the way up to iron. So far, this process has created all the common elements, which make up 99 percent of the Earth and everything on it.

Because it takes so much energy to fuse iron atoms, once the heart of the star is solid iron, the star implodes – and that material then rebounds out in a spectacular explosion known as a supernova. The tremendous energy of the supernova then fuses heavier, rare elements, like gold, copper, zinc, and platinum.

But that's not the only place those elements are made. They are also created in the collisions of super-dense neutron stars, which cram huge volumes of matter into very small spaces. (Think of our sun crammed into a sphere only 10 kilometres across.)

When two neutron stars crash into each other, they rip each other apart and spew out a cloud of neutrons that go through radioactive decay. That decay process, which scientists call the "r-process", changes their chemical identities and produces half of the heavy elements. Scientists finally got evidence of this process in 2017 when they recorded the collision of two neutron stars in the Hydra constellation.

So next time someone says that we are all made of star stuff, you can tell them they are absolutely right!

– Tenille Bonoguore

Ontario PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS Canada

www.perimeterinstitute.ca